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PROCEEDINGS OF RESEARCH CONFERENCE ON: HIGH-TEMPERATURE DRYING --ETC(U)
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Proceedings of the Research Conference on:

HIGH-TEMPERATURE DRYING EFFECTS ON MECHANICAL PROPERTIES OF SOFTWOOD LUMBER

Held Feb. 25-26, 1976
at Madison, Wis.

Proceedings Compiled and Issued at
Forest Products Laboratory
Forest Service
U.S. Department of Agriculture

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Proceedings of Research Conference on:

HIGH-TEMPERATURE DRYING EFFECTS ON MECHANICAL PROPERTIES OF SOFTWOOD LUMBER,

Held 25-26 February 1976 at Madison, Wisconsin,

Proceedings Compiled by:
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Madison Wis

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FOREWORD

Many softwood producers in the United States and Canada are using high temperature kiln drying for softwood construction lumber. Advantages of short drying times and low energy costs can be expected to spur further rapid growth in high temperature drying. In addition to these important processing concerns, the dryness level relates to the allowable design properties associated with the lumber; lowering the moisture content of lumber increases its strength and stiffness.

At the present time, allowable properties for structural softwood lumber are linked to the drying process only by levels of dryness achieved. Limited research, however, has indicated that certain high temperature drying procedures may cause a marked reduction in selected mechanical properties of some wood species. Other species do not seem to be significantly affected by similar drying procedures. If some high temperature methods are deleterious to some strength properties, provisions may be necessary to adjust allowable properties for lumber dried by these methods.

These concerns for the interaction of drying with properties had been noted by several organizations active in drying research. These researchers also were aware, however, that possible negative interactions between drying procedures and properties had not been verified for many of the species and drying schedules of commercial interest, and, furthermore, that optimum drying procedures may be identified through research.

To achieve a better understanding of the status of high temperature drying and property research and to provide a format for deliberate research planning, the U.S. Forest Products Laboratory invited organizations conducting lumber drying and mechanical property research to a 2-day research conference at the Forest Products Laboratory, Madison, Wis., to discuss relevant research results and further research needs. Other organizations unable to send a representative indicated a high degree of interest.

The conference objectives were specifically to (1) develop a position paper of current knowledge on the effects of high temperature kiln drying on mechanical properties and degrade of softwood lumber (2) prepare a statement of research needs, (3) establish a research steering committee to coordinate and guide high temperature drying research toward high temperature drying procedures that would maximize drying efficiency and minimize effect on wood properties, and (4) to aid in communicating relevant results to concerned industry groups.

This proceedings documents the conference's attempt to satisfy the objectives. It includes the papers presented at the Conference, contributed information, a bibliography, and a tabular summation of reported mechanical property effects of high temperature drying. The needs for further research were extensively discussed, and a tentative consensus on research needs, also included in these proceedings, was agreed upon.

Rather than a steering committee, the conference established a Coordinating Committee to aid in guiding further research.

William G. Galligan and
Erwin L. Schaffer, FPL

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Participants
in conference on

High-Temperature Drying Effects On

Mechanical Properties of Softwood Lumber

Conference Co-Chairmen: John M. McMillen &
Charles G. Gerhards,
U.S. FPL

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J. F. Graham Mackay, Western Forest Products Lab., Vancouver, B.C., Canada
Christian Skaar, State University of New York at Syracuse on leave to Virginia Polytechnic Institute and State University, Blacksburg, Va.
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I. INDUSTRIAL HIGH-TEMPERATURE DRYING

INTRODUCTION

By

J. M. McMillen

The present use of high temperature kiln drying for softwood began about 15 years ago. It was limited to poles and studs. Research at Vancouver, B.C., and Corvallis, OR, indicated there was enough strength loss in Douglas-fir, white fir, and western hemlock to discourage more widespread use for construction lumber. Recently, however, there has been a great upsurge of interest in high temperature drying because of a growing demand for new dry kilns, a great need for conserving energy, and significant benefits of high temperature drying in warp reduction.

Before getting into the position papers on high temperature drying effects, a brief discussion was held concerning the present industrial high-temperature kiln drying situation. Two speakers were invited to cover specific regions. Dr. Peter Koch, Chief Wood Scientist, Southern Forest Experiment Station, Pineville, LA, who realized the great potential of high temperature drying for southern pines, discussed the situation in the southern states. Charles J. Kozlik, Associate Professor, Oregon Forest Research Laboratory, Corvallis, OR, who conducted much of the early kiln drying strength evaluations and has expressed concern about apparent recent disregard for strength effects, discussed the situation in the West. Other participants spoke briefly about commercial developments in Canada.

Included in this section are remarks made later by Paul Bois, Wood Drying Specialist, State and Private Forestry, U.S.F.S., about southern pines and by myself on actual drying conditions during commercial high-temperature drying of lodgepole pine and western larch studs, plus some information from kiln manufacturers.

COMMENTS: SOUTHERN UNITED STATES

by Peter Koch

High-temperature drying of southern pine and Monterey pine lumber is quick, simple, effective, and economical. When effective restraint against warp is applied, e.g., a top load of 200 pounds per square foot, grade and value of lumber so dried is significantly higher than grade and value of matched lumber conventionally stickered and dried at temperatures below the boiling point. Lumbermen on two continents (Australia and the United States) have converted wholesale to the new technique. The degree of diminution of mechanical properties is not of practical significance. Twelve years of research, 21 publications (five relative to mechanical properties), and one manuscript in process support these conclusions.

The 12-year (1963-1975) series of experiments on high-temperature drying and concomitant warp control of southern pine lumber conducted at the Pineville laboratory of the Southern Forest Experiment Station has completely altered kiln-drying procedures for southern and Monterey pines.

In 1963 in the United States, 8/4 southern pine was dried on 5- to 7-day schedules with temperatures not exceeding 200° F. In 1965 the Pineville laboratory designed a 240° F kiln with cross-circulation velocity of 1,000 feet per minute. The kiln was ordered in early 1966 and was in operation by the end of that year. Our research yielded methods for controlling warp and improved earlier results obtained in a 230° F kiln by Walker Wellford, Jr., Research and Development Manager for Moore-Oregon in Memphis, TN. The technique developed for 1.75-inch lumber involves drying narrow loads (about 4 feet wide) under restraint, with cross-circulating air at a velocity

of 1,000 feet per minute. Dry-bulb temperature of 240° F and wet-bulb temperature of 160° F is maintained for 21 hours. The lumber is then conditioned for 3 hours at 195°/185° F. Final moisture content is about 9 percent. In 1967, Mr. Wellford, displayed at the New Orleans Machinery Show a typical straight southern pine stud cut from a veneer core dried by the Pineville process.

Stimulated by that demonstration and subsequent research findings, the industry began a massive and almost total shift to high-temperature kilns for southern pine. Today, kiln manufacturers in the South offer high-temperature equipment almost to the exclusion of kilns operating below the boiling point.

From 1965 through 1967 a number of Australian lumbermen came to Pineville to see our kiln-drying and warp-control experiments. These industrialists saw the results we were obtaining with 240° F drying under restraint, and returned to Queensland to apply the technique to slash pine (*Pinus elliottii* var. *elliottii*) grown there. The success of the technique was so immediately apparent that it was promptly applied to lumber from plantation thinnings of Monterey pine (*Pinus radiata* D. Don.). Until this technique was introduced, pine lumber from thinnings in Australia--especially Monterey pine--exhibited so much warp (particularly twist) that it was virtually unmerchantable. The Pineville technique so completely solved the Australian problem that by late 1974 every pine mill in Australia used the high temperature schedule (in some mills preceded by a short steaming period). The result has been complete acceptance of the exotic pine species (slash, Monterey, and Carribean)

by the Australian market.

Details of one Australian operation are as follows:

Species: Pinus elliottii

Lumber thickness: 2-1/8 inches

Kiln length: 32 feet

Load width: 4 feet (Experience indicated 5-foot loads were too wide.)

Load height: 6 feet

Sticker thickness: 1-1/8 inch (Experience indicated these thick sticks gave better results than 3/4-inch-thick sticks.)

Holding capacity: 5,000 board feet

Top load: 12-inch thick concrete slab

Side restraint: Before the top load is applied, the edges of the load are rammed with bumper devices on both sides. Because of non-uniform lumber widths, the bumpers are only partially successful in smoothing load edges.

Fans: Five 8 hp. fans circulate air at 1,000 feet per minute. Fans are reversed every 2 hours.

Schedule: 2 to 4 hours of initial steaming; 24 hours at 240° F dry-bulb temperature and 160° F wet-bulb temperature; 3 to 4 hours of steam conditioning. Total: About 30 hours.

Final moisture content: 10 percent

Twist in dry boards: Average 0° with ± 5° range. This firm uses

a loading frame warped 3° in a direction opposite to the usual lumber twist, with the surface of the concrete top load also warped in the same direction. Other mills use flat loading frames; all use concrete top loads.

Unlike the Australians, the U. S. Industry has been less rigorous in following research recommendations. Loads are generally 8 feet wide and unrestrained, and within-load variation in lumber thickness is often substantial. A variety of schedules is used. While the new kilns are capable of air velocities through the load in the 600 to 800 foot-per-minute range, the velocities that are actually attained often are lower because of poor attention to the details of baffling. Drying times for 8/4 lumber to reach the prescribed maximum moisture content levels of 19 or 15 percent, therefore, are in the neighborhood of 28 to 36 hours. These longer times are necessary to get the center of the wide loads dry. Warping is somewhat greater, also, than that obtained in loads heavily top loaded with concrete.

Presently we are working on a 270° F/185° F continuous kiln to dry 5-foot wide loads of lumber under restraint (a moving top load) in 8 hours followed by 3 hours of conditioning at $195^{\circ}/185^{\circ}$ and 1 hour of forced-draft cooling at ambient temperature. Air velocity in the drying zone begins at 1,600 feet per minute and ends at 1,000 feet per minute. Final moisture content for 1.75-inch thick green southern pine should average about 8.5 percent with standard deviation of about 2 percent. A major kiln manufacturer will supply a kiln of this design, with capacity of 500,000 board feet per week, for about $250,000. This tentative price does not include stickers ($1\frac{1}{4}$-inch thick) or handling or firing equipment.

(Dr. Koch showed several slides of the equipment used in developing the 21-hour-240° F schedule; also shown were slides describing the new tunnel kiln and green bark burners he has designed to direct-fire the kiln.)

COMMENTS: WESTERN UNITED STATES

by Charles J. Kozlik

Kiln drying of 2-inch dimension lumber is increasing each year in the United States. In 1973, 20,211,000,000 board feet, or 65 percent of the total production of softwood lumber, was kiln dried. About 10,905,000,000 board feet, or 54 percent, of the total kiln-dried lumber was 2-inch dimension. Projected figures for 1973 indicate that 10,250,000,000 board feet, or 94 percent, of kiln-dried dimension lumber was used in construction of mobile, packaged or modular, and conventional and multifamily homes and laminated beams (includes 1-inch lumber for curved members). These figures were compiled from references for a project initiated at the Forest Research Laboratory.

Although I have not compiled data on production and use of dimension lumber in 1974 and 1975, I believe the percentage of kiln-dried lumber and its use would not vary greatly from the figures for 1973 because of the depressed lumber market. During 1973 and extending to 1975, major kiln manufacturers on the west coast sold high-temperature kilns with a holding capacity of 16,943,000 board feet. During this period, low-to-high temperature kilns were sold for a capacity of 7,380,000 board feet. These manufacturers market kilns throughout the United States and one manufacturer sold high temperature kilns in the southern pine region with a holding capacity of 7,279,000 board feet. Naturally, some high-temperature kilns were sold before 1973, and most kilns sold to dry lumber at temperatures below 200°F have the ability to dry at temperatures up to 230°F. Therefore, there is no way to approximate the volume of dimension lumber now being dried at temperatures above 212°F. Many installations have kiln

recorder-controllers, valving, air velocity, and heating capacity to dry at temperatures exceeding 230° or 240°F. Although the kiln manufacturer will recommend a maximum dry-bulb temperature of 230°F, some lumber producers are drying at 260°F with rumors of going as high as 300°F.

QUESTION: (Comstock) Haven't most people discontinued drying Douglas-fir at high temperatures?

ANSWER: (Kozlik) I have found them using high temperature on 2 x 4's and 2 x 6's; not on larger sizes.

QUESTION: (Galligan) What percentage of western softwood lumber is redried?

ANSWER: (Kozlik) About 16 to 20 percent in northern California; 10 to 15 percent in western Oregon.

COMMENTS: EASTERN CANADA

by Donald R. Huffman

Experiments on high temperature drying were initiated at the Eastern Forest Products Laboratory in the early 1950's, and tentative drying schedules were published for six eastern softwoods. In 1962, emphasis shifted to hardwoods. Further research on softwoods began again in 1966 with plantation-grown red pine. The continuing program has included eastern spruces, jack pine, and balsam fir. In each case, the initial objectives were to obtain a substantial reduction in drying time with no increase in degrade, and not attempt to evaluate the economics or strength effects.

On a commercial scale, mills in eastern Canada have been slow to accept high temperature drying as an alternative to conventional kiln drying. However, on the basis of drying time and lumber quality alone, a few progressive mills have decided in favor of high temperature drying facilities, while a number are operating over a range from elevated conventional to high temperature depending on fluctuations in available energy.

The general schedule is 240°F dry-bulb temperature, 200°F wet-bulb, time 24 hours. This works very well with the eastern spruces and jack pine. Balsam fir is a problem because of zones of wetwood which often develop severe drying defects. If we could develop a way to sort out balsam fir, the door to widespread use of high temperature drying will be open. Eastern hemlock cannot be dried successfully by high temperatures because the shake common to this wood leads to excessive degrade.

COMMENTS: WESTERN CANADA

by J. F. G. Mackay

In the lumber industry in Western Canada high-temperature drying is not widespread, although new kilns frequently have provision for operating at high temperatures. Almost exclusively only 2 x 4 and 2 x 6 lumber is dried in constant high temperature schedules, and the principal species involved are Western white spruce, lodgepole pine and alpine fir, and to a lesser extent Douglas-fir and Western hemlock.

Dry-bulb temperatures have been in the neighborhood of 230°F and 240°F, following schedules recommended by Moore-Canada. Not more than 10 percent of the kiln dried western softwoods in Canada are dried by high temperature.

There have been proposals to use the practice of "redrying" for some Western species, particularly those prone to wet pockets. This would entail segregating insufficiently dried lumber prior to planing, and returning this material for further kiln drying. It could be possible therefore to subject lumber to excessively long periods of high temperature and so cause strength reductions.

OBSERVATION: SOUTHERN PINES

by Paul J. Bois

I have visited several high temperature drying installations in the South, and can attest that high temperature drying is used extensively for southern pine. At one installation I saw an experiment on heavy top weighting of the load. This certainly held warping to a minimum.

Another mill operates two 9-hour shifts, producing 175,000 board feet of pine dimension a day. They have two high-temperature kilns operating on a 26-hour cycle. Steam pressure is 150 psi. The boiler is fueled by a green-sawdust system that has operated successfully over a 4-year period. The kiln has cam-operated controllers which appear to be a modified CRT system with a final temperature of 240°F. Our meter test on some of the cool lumber showed it to be at 20 percent moisture content.

I'll show you some slides of another installation of a 100,000 board foot high temperature kiln in Louisiana direct fired by an Energex system using dry shavings for fuel. The burner produces 20 million BTU's per hour. The control instruments include six heat-sensing elements in the kiln and a number of safety features to monitor the flame temperature so as to prevent any accidental kiln fires. All products of combustion go directly into the kiln. The lumber has a slightly darkened surface which appears to surface off cleanly.

The air in this type of kiln is under considerable pressure from the blower system and steam escapes from around the doors and vent caps. The immense clouds of escaping steam are a common sight with this type of system.

The fuel system will pay for itself in 2 years, based on present costs of natural gas at \$.65 per therm. Oil and gas burners are available on standby, but the system has operated without breakdown for over a year.

INDUSTRIAL DRYING OF

LODGEPOLE AND WESTERN LARCH

by J. M. McMillen

Kimball and Lowery (1967) obtained information on temperatures in a 80,000 board foot high-temperature kiln during the drying of lodgepole pine and western larch studs. The dry-bulb and wet-bulb temperatures, as indicated by the recorder, when drying western larch are shown in figure 1. Three to four hours were required to get up to temperature. In the method of operation used, the vents were opened at 4 hours, and the wet-bulb temperature fell. Temperatures by thermocouples at different longitudinal locations in the kiln at 5, 9, and 22 hours are shown in figure 2. At 5 hours there was considerable temperature variation; at 22 hours most of the kiln was over 240°F. The 22-hour drying time was not long enough to get the western larch studs dry (figure 3). The average moisture content of lodgepole pine studs was about low enough, but some of the core moisture values were still high at the end of 22 hours of drying (figure 4). Total degrade from high temperature drying was about the same as that from conventional drying for both species. Warping was slightly less, but surface checking was slightly more from the high temperature drying.

Industrial high temperature drying is relatively new and practices have not become standardized. In a manual directed largely at conventional kiln drying (Knight 1970), some high temperature or elevated-high temperature schedules are outlined. Species, temperatures, and times are:

2-inch white fir, sap and corky--210°-240°F, 29 hours (plus 6 hours equalizing when needed)

2 x 4 white fir or hemlock studs--212°-240°F, 30-36 hours (redry sinker)

2 x 4 lodgepole pine--210°230°F, more than 24 hours (plus 4 hours equalizing in some cases)

2 x 4 Engelmann spruce--200°-210°F, 22-26 hours or until dry.

4 x 6 white fir decking--220°-235°F, more than 96 hours.

There are three major kiln companies and six or more minor companies selling high-temperature kilns in the United States. Two of the major companies have both an eastern and a western office. The following general information on drying was obtained by telephone from four of the five major offices:

Major Office A.--Most high temperature kilns supplied are for southern pine; although some are for lodgepole pine studs. Western hemlock and Douglas-fir mills do not favor high temperature drying because of moisture variability problems; the long kiln time needed to comply with maximum moisture content of 19 percent for these species leads to a great amount of visible degrade. Temperature maximum in high temperature kilns is 240°F generally. Users are limited to 250°F maximum by the top temperature rating for the internal kiln fan motors used. One kiln motor manufacturer, however, claims a 275°F top.

Major Office B.--Temperatures used experimentally and in practice for southern pine are 235° to 240°F. Motor temperature limitation is 250°F. Air velocities up to 900 ft/ min. have been used experimentally; they are about 600 ft/min. in commercial practice. The time required for 19 moisture content maximum is 26 to 28 hours. Customer concerns are production rate and appearance (degrade).

Major Office C.--Some high temperature kilns are built when requested. Maximum temperature limit is 250°F, but most kilns are not operated at that high a temperature. No highly-adverse strength effects have been found.

Major Office D.--High temperature dry kiln instruments are "red lined" at 240°F. No specific information is available on air velocity or drying times for western species. Some direct-fired kilns are produced and these are easily capable of temperatures higher than 250°F, if fan motors are outside of kiln.

The one minor kiln company contacted is expanding its business greatly. Maximum temperatures in its kilns are in the 230°-240°F range.

A representative of the major company producing the CRT process stated that a general scheme for drying by this process is to start at 170°F and raise temperature gradually to 230°F or 240°F. Exact rate of temperature rise and final temperature vary with the species. Rapid drying during the first part of the schedule is obtained by high air velocity through the load and high rates of powered supplemental-air ventilation. Species dried and drying times for 2-inch dimension lumber are:

Douglas-fir: 45-55 hours, plus equalizing

White fir: 36-38 hours

Western hemlock: 42-48 hours

Other species dried by this process but without time data available are lodgepole, ponderosa, and red pine and Engelmann and white spruce.

One of the major kiln company representatives stated that three companies providing fire insurance for kilns have set maximum temperature limits for direct-fired kilns as follows:

At controlling instrument bulb - 275°F

At motor frame - 290°-300°F

In mixing chamber for flue gas and kiln air, 450°F reduces burner to low flame, 490°F shuts burner off.

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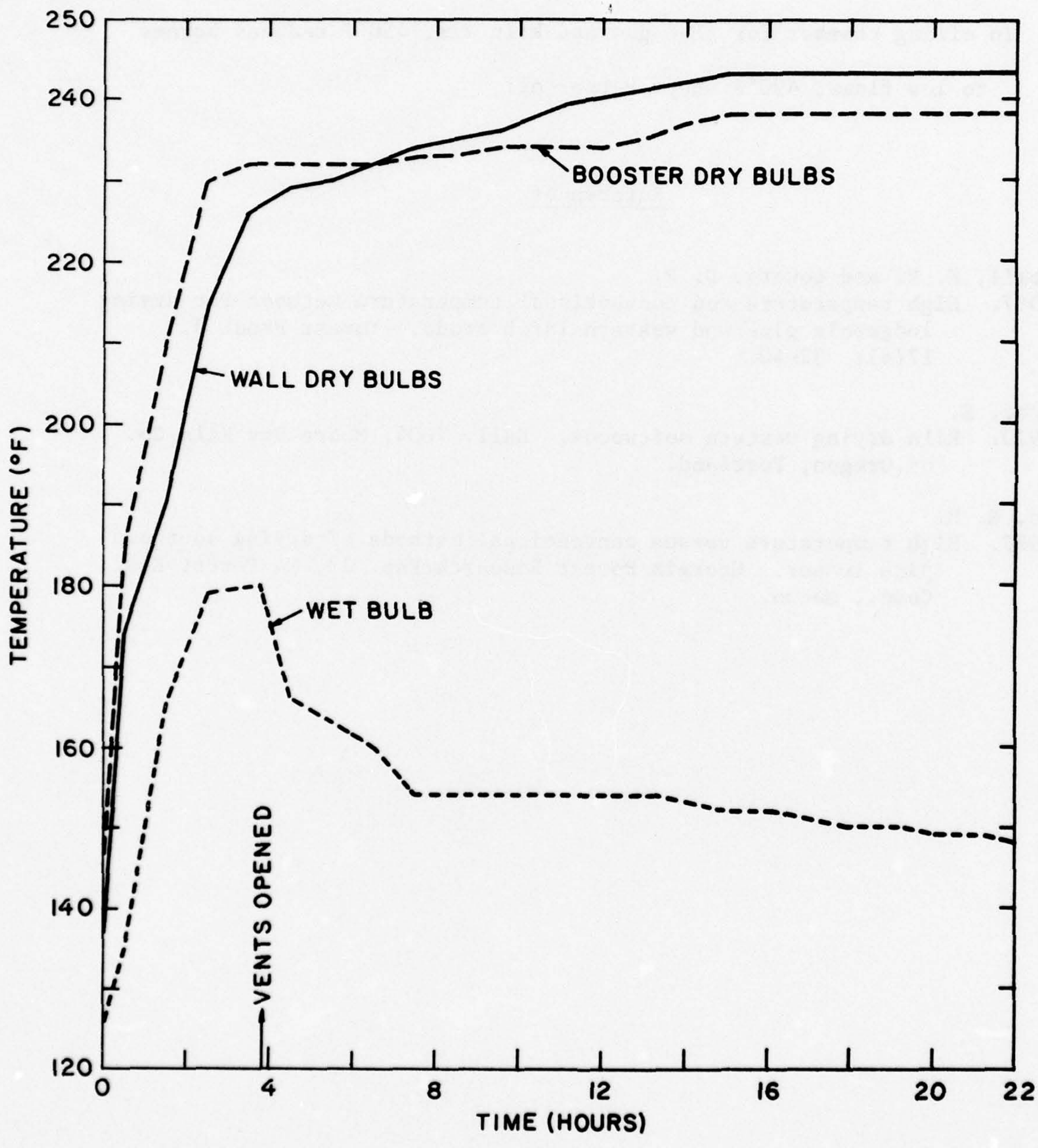

Figure 1.--Recorded dry- and wet-bulb temperatures during high-temperature drying of a commercial charge of western larch studs. (M 144 548)

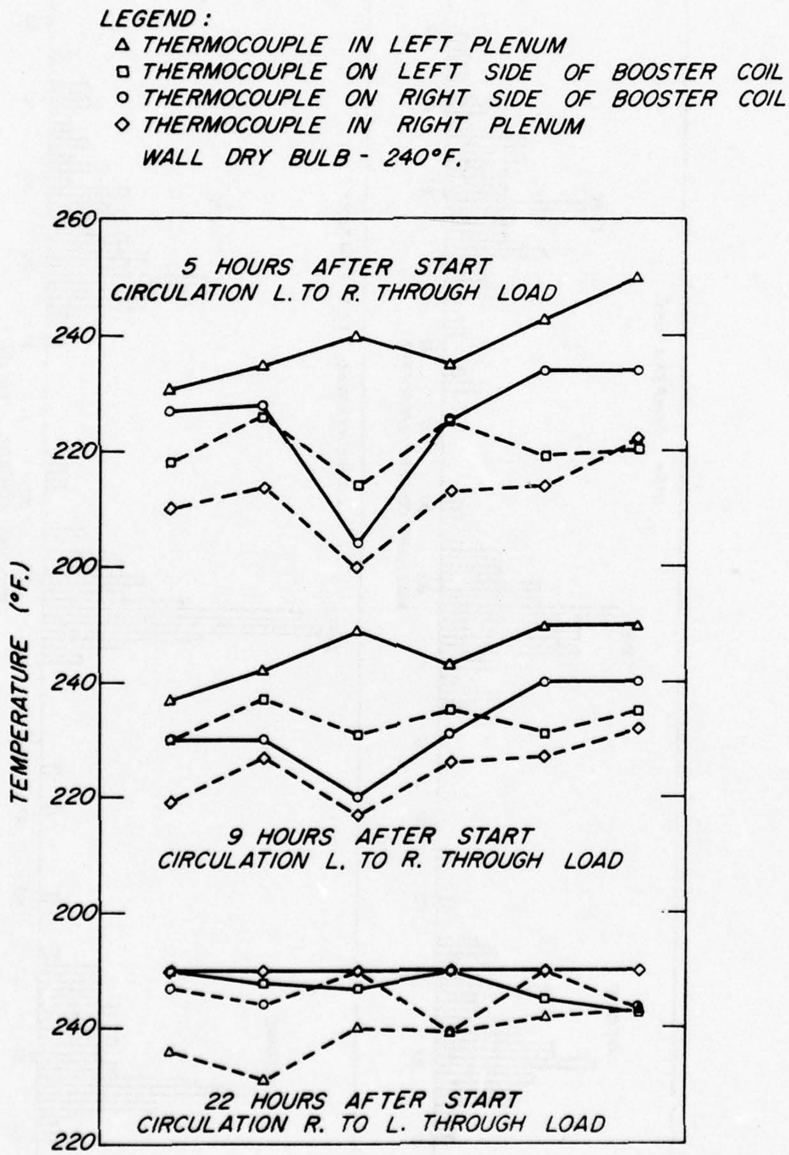

Figure 2.--Temperature variation along length of kiln after 5, 9, and 22 hours of high-temperature drying of western larch studs. (M 130 784)

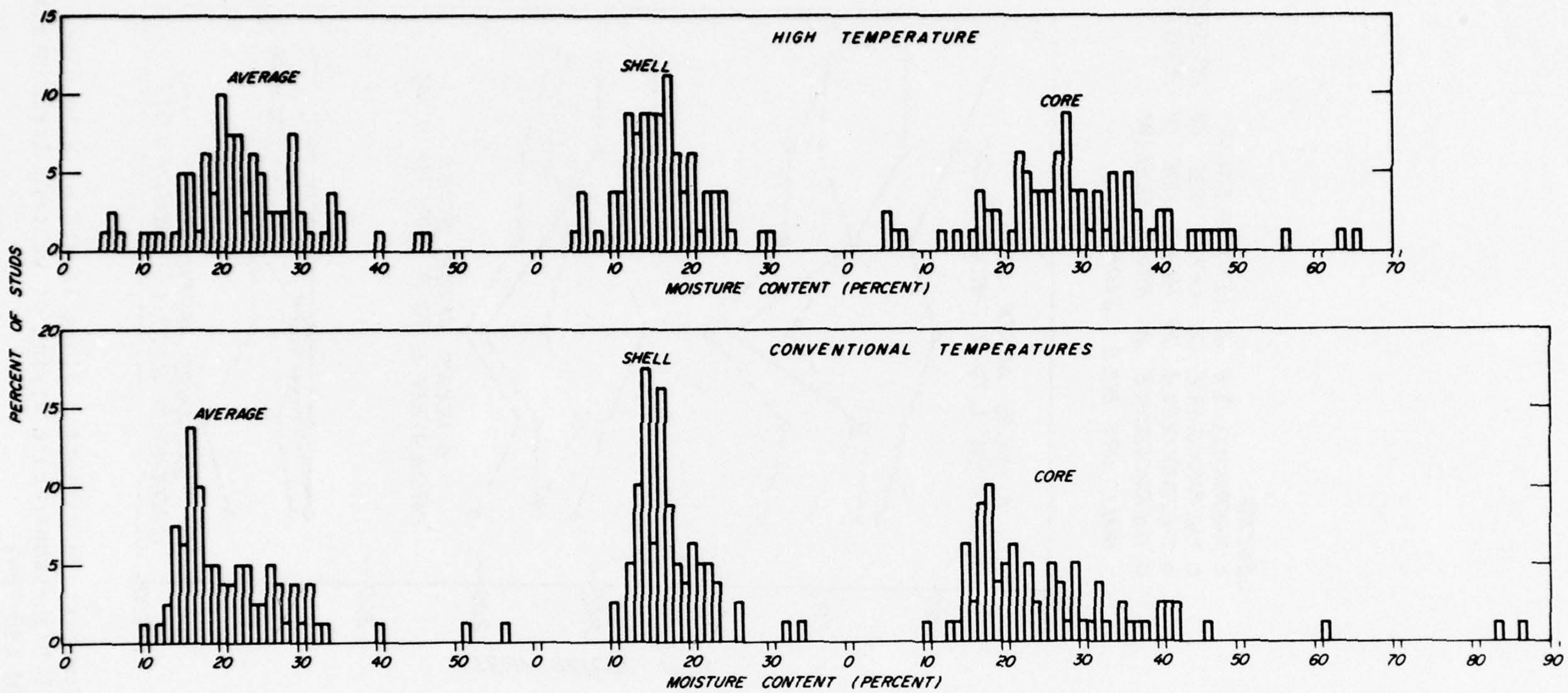

Figure 3.--Frequency distribution of average moisture content values (oven test) of western larch studs after 22 hours of high-temperature drying, or 96 hours of conventional temperature drying. (M 130 787)

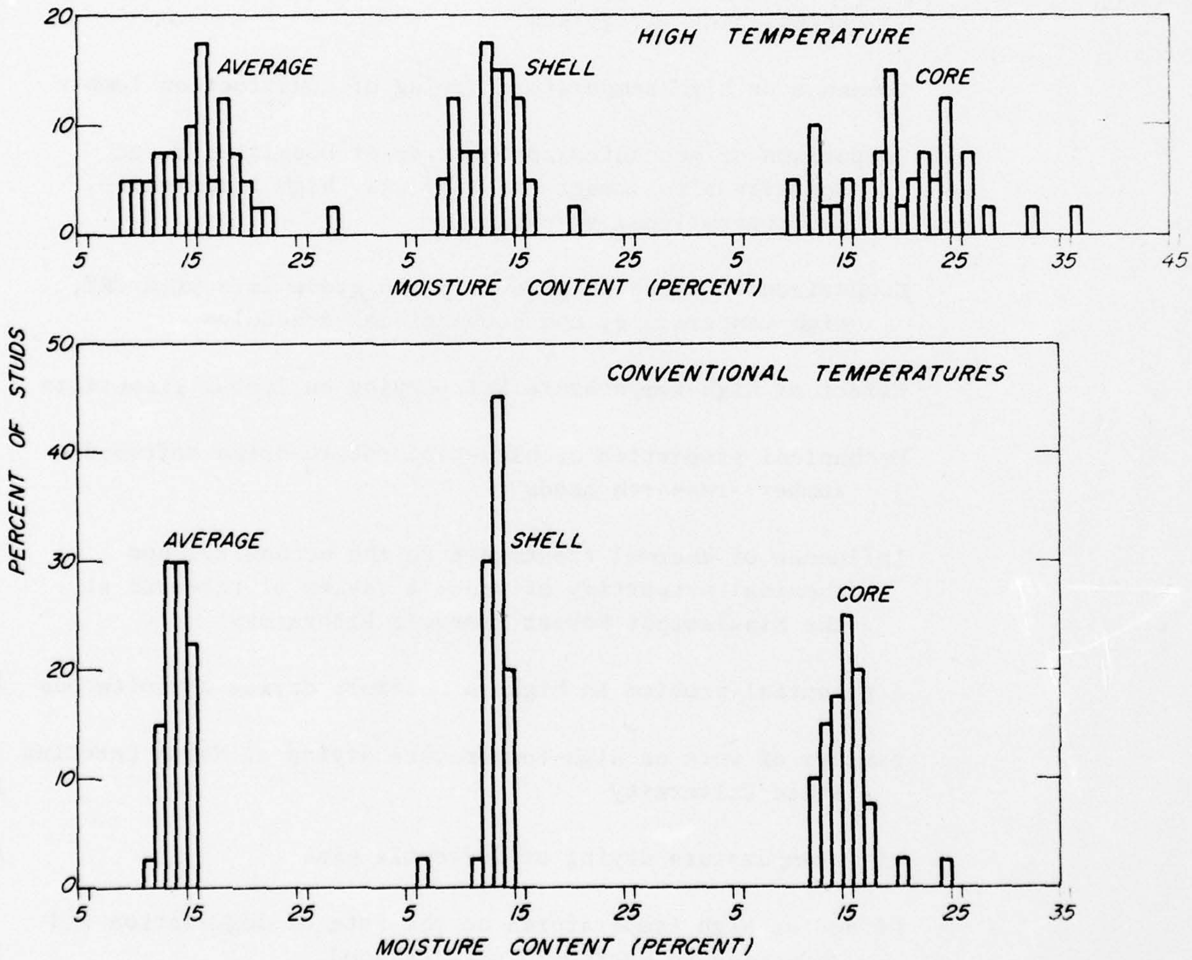

Figure 4.--Frequency distribution of core moisture content values (oven test) of lodgepole pine studs after 22 hours of high-temperature drying, or 96 hours of conventional temperature drying. (M 130 783)

II. POSITION PAPERS ON HIGH-TEMPERATURE DRYING EFFECTS

INTRODUCTORY COMMENTS

By

C. C. Gerhards

In setting up this research conference, the co-chairmen invited participants to prepare position papers on where they thought research stood on the high temperature drying effects on mechanical properties of lumber and what they thought were research needs. While almost all participants prepared and presented position papers on current knowledge, less than half prepared research needs statements.

The presented position papers on current knowledge and research needs follow. Included are a paper by the Lumber Seasoning Unit of the EFPL, Ottawa, Ontario, commenting on high temperature drying, and a letter expressing D. G. Arganbright's thoughts on research needs.

EFFECT OF HIGH-TEMPERATURE DRYING SOFTWOODS ON THE MECHANICAL PROPERTIES OF WOOD

Charles J. Kozlik

INTRODUCTION

Lumber dried at high temperatures may not be of concern for some end uses. Where design criteria are important, such as for laminated beams or trusses, the effect of drying temperature on mechanical properties should be of concern to standard setting agencies, to design engineers, and in the wood products field.

STRENGTH STUDIES

Literature on the effect of temperature on strength properties of wood has been summarized by Arsenault (1) and Salamon (11). In 1975, the Institute of Wood Science, CSIRO, in Australia, conducted a seminar on high-temperature drying. Several studies have been made at the Forest Research Laboratory, Oregon State University.

Eddy and Graham (2) investigated the effects of drying on strength properties of 2-inch clears of Douglas-fir. Temperatures included 75°F (control) and 140°F and drying with three organic liquids at temperatures of 190, 225, and 250°F. Strength properties investigated included static bending [modulus of rupture (MOR), modulus of elasticity (MOE), work to proportional limit, and work to maximum load], compression perpendicular to the grain, and side hardness. Results, as shown in Table 1, indicate MOE was least affected and work to the maximum load was most affected.

Increasing temperature had a corresponding decrease in all strength properties studied, except MOE.

Graham (3) investigated the effect of drying on bending properties of 1-inch clears cut from 4- by 8-inch Douglas-fir timbers that were dried in air at 75°F (control), 153°F, and 202°F, and with xylene vapors at 220°F. Strength properties investigated were static bending (MOR, MOE, and work to maximum load) and toughness. Table 2 summarizes the results from kiln drying at 153°F to kiln drying at 202°F and with xylene vapors at 220°F. Results indicate MOE was least affected and work to maximum load was most affected. Increasing temperature had a corresponding decrease in the strength properties studied.

Kozlik (7) studied the effect of temperature, conditions for equilibrium moisture content (EMC), and time on the strength of Douglas-fir and western hemlock 1-1/2-inch clears. Temperatures selected were 90°F (control), 150, 180, 195, 215, and 230°F. At each temperature, conditions for EMC of 6 or 12 percent were applied. The effect of time was studied by doubling the drying time required at each temperature (except 90°F) with conditions for EMC of 6 percent. The strength properties investigated included shear parallel to the grain, oriented radially and tangentially; static bending (fiber stress at proportional limit, MOR, and MOE); and toughness, oriented radially and tangentially.

Before testing, the specimens had to have slope of grain no more than 1 inch in 20; be free of shake, rot, pitch, knots and areas of concentrated pitch; and have seven or more rings per inch.

Effect of kiln conditions on the strength properties was studied by a factorial experiment with replications based on specific gravity. Each Douglas-fir charge contained 29 specimens and 35 specimens of western hemlock.

The strength properties were affected in various magnitudes, as shown in Table 3, at drying temperatures from 150 to 230°F. Toughness had a reduction of 15 to 25 percent; shear and MOR about 10 percent; fiber stress at proportional limit from 3 to 10 percent; and MOE was 3 percent or less. Generally, the effect of time or prolonged heating had lower strength values.

Kozlik (8) investigated the effect of kiln temperatures on the bending strength of 2- by 6-inch Douglas-fir and western hemlock dimension lumber; temperatures applied included 70°F (control), 170, 200, and 230°F. The bending properties studied were MOR and MOE.

The lumber selected had to have slope of grain no more than 1 inch in 16; be free from shake, split, rot, and areas of concentrated pitch, and with assignment of strength-ratio (SR) classes of 40, 60, and 80 percent.

The strength ratios were assigned according to ASTM Standards D 245-67, with the critical knots in the middle third of the total span. No other defects affecting strength were accepted. Effect of temperature on bending properties of the seasoned lumber was studied by a randomized block design with replications based on values for MOE of unseasoned pieces within each chosen strength ratio class. Each Douglas-fir kiln charge averaged 38 specimens and there were 46 specimens for each western hemlock kiln charge. The lumber was tested in static bending by the procedures set forth in ASTM Standards D 198-67.

Table 4 summarizes the results from kiln drying at 170°F to kiln drying at 200 and 230°F. Modulus of elasticity of Douglas-fir and western hemlock was reduced by 2 percent or less. The MOR of Douglas-fir was reduced by 15 to 21 percent and 10 to 14 percent for western hemlock.

Effect of drying temperatures on tension parallel to the grain was studied by Kozlik (9) on 2- by 6-inch Douglas-fir and western hemlock

dimension lumber. The kiln temperatures selected were 170, 200, and 230°F. After drying and machining, selection of the test specimens was made according to ASTM Standards D245-74. Two edge-knot classes (located on the wide face), small (from 3/4 to 1 inch) and large (from 1-1/4 to 1-1/2 inches), were selected for each species and kiln temperature. There were 33 small knot and 34 large knot specimens of Douglas-fir and 32 specimens for each knot class of western hemlock for each temperature.

Strength comparisons (Table 5) in drying from 170 to 230°F showed Douglas-fir with small knots was reduced by 11 percent and with large knots was reduced by 22 percent; western hemlock with small knots was reduced 21 percent, and with large knots by 2 percent. The lines of regression for each knot class and species were determined, but the correlation coefficients were low and ranged from 0.03 to 0.18.

Effect of temperature on tensile strength of seasoned specimens was measured by an analysis of covariance, which included the three test temperatures for each knot class and species. Nine properties were measured as covariates: knot size; MOE, specimens dry and loaded flat at the test knot; specific gravity, based on oven-dry volume and weight; MOE in tension; moisture content at the time of test; localized grain deviation around the knot; rings per inch; percentage of summerwood; and percentage of compression wood in the cross section. The analysis of covariance determined the degree of correlation, both singly and in combination of the forementioned properties, with tensile strength. The best combinations of covariates did not result in correlation coefficients any greater than 0.22 to 0.41

The range of tensile strength values and coefficients of variation (average 26 percent) is large, but not out of proportion considering the

range of test values for clear lumber and dimension lumber shown by Johnson and Kunesh (5). Although rigid restrictions are placed on selection of specimens, tension parallel to the grain appears to be a strength property difficult to predict. Also, in selection at the mills of Douglas-fir lumber for this study, some samples were rejected for abnormal grain distortion in the knot area. This was true in past studies at the Forest Research Laboratory; for a given knot size, there is greater distortion around the knot in Douglas-fir lumber than in western hemlock or hem-fir lumber. Consequently, 82 percent of the Douglas-fir specimens in this study had encased knots, but only 37 percent of the western hemlock had encased knots. This illustrates the difficulty of meeting sample selection restrictions where grain distortion around the knot is a factor.

Table 6 summarizes results of all the various studies made at the Forest Research Laboratory.

Effect of high temperature drying on degrade has received attention by several investigators. Personnel in public agencies, private companies, and kiln manufacturers have the knowledge to regulate high-temperature kiln schedules to minimize degrade or have it be equal to that from conventional drying of our indigenous species. Therefore, I believe this area should not be of concern at this conference.

RESEARCH NEEDS

My comments on future research on the effect of drying temperature on the mechanical properties of wood will be confined mainly to softwoods indigenous to western North America. The mechanical properties of importance include static bending (MOR and MOE), shear, and tension parallel to the grain. Compression perpendicular and parallel to the grain are important design criteria and possibly should receive more attention.

Mechanical properties of Douglas-fir have received attention at the Forest Research Laboratory, Oregon State University, and the Western Forest Products Laboratory, Vancouver, B.C. Although several properties were investigated, effect of temperature on bending strength has been, in my opinion, fully explored for coast type Douglas-fir. Both small clears and full-size lumber specimens have been tested and the results are in agreement. Possibly, additional work is required on shear and compression parallel and perpendicular to the grain. The shear values investigated at the Forest Research Laboratory had conflicting results, but further analysis may provide more positive results.

Studies made at the Forest Research Laboratory on the effect of temperature on tension parallel to the grain of Douglas-fir and western hemlock had conflicting results. Therefore, additional research on 2- by 6-inch clears or lumber containing natural defects, only knots, is being suggested to supplement the previous work. Selection and matching of lumber specimens containing knots for testing tension parallel to the grain is most difficult.

Mechanical properties of western hemlock have been tested by the laboratories in both British Columbia and Oregon but results are not in agreement. The work cited on the temperature effect on western hemlock at the Forest Research Laboratory was done only on western hemlock with the true firs, *Abies*, excluded. Results of static bending (MOR and MOE) on small clears and 2- by 6-inch lumber are nearly equal. Therefore, the question arises as to whether the two species should be separated or combined. In either instance, past research would require reevaluation, and additional testing is needed.

Small clears cut from western larch and lodgepole pine poles were tested in static bending and toughness by Lowery and Rasmussen (10) but drying temperatures averaged 200°F. Reduction in static bending properties (MOE and MOR) did not exceed 10 percent for either species. Troxell and Luza (13) tested small clears cut from lodgepole pine studs dried at 220°F. The results indicate a small reduction (3 percent) in shear and no reduction in static bending (MOR and MOE). At present, both species are being kiln-dried at temperatures above 212°F and used in laminated beams and trusses. Therefore, a testing program including static bending, compression and tension parallel to the grain, compression perpendicular to the grain, and shear is needed.

Spruce, cottonwood or aspen, ponderosa pine, redwood, and cedars are being used for light framing. Spruce and ponderosa pine are kiln-dried at high temperatures, but I am not familiar with the scope of past research and believe only the Western Forest Products Laboratory has worked with spruce. I believe the end use of these species would probably dictate the testing program.

Consideration should be given to the effect of kiln-drying poles. There is a movement to kiln dry poles before treatment, and pole producers are using or contemplating drying temperatures above 212°F. The Forest Research Laboratory is investigating kiln drying schedules (180 to 260°F) for Douglas-fir poles, is testing small clears in static bending cut from pole sections, and has material for compression parallel to the grain if such tests would be desirable. Although no results are available, maximum loads in static bending indicate that poles dried at 230°F may show reductions of 20 percent in MOR.

With the apparent increase in kiln drying above 212°F of southern pine dimension lumber, a testing program and revaluation of past studies is

required, especially in light of research by Koch (6), Thompson (12), and Wood, Erickson, and Dohr (14). Koch tested southern pine studs dried at 180 and 240°F in static bending (MOE, MOR, and fiber stress at proportional limit). By analysis of variance, the strength properties were not significantly different between the two drying treatments. The standard deviation for MOE averaged 455,000 and the coefficient of variation averaged 29 percent, however. The standard deviation for MOR averaged 3,310 and the coefficient of variation averaged 48 percent. This variation of test values suggests that an analysis of variance would not show significant differences.

Thompson showed a reduction of 25 percent for MOR in bending for poles and small clears cut from poles that were kiln-dried at 152°F as compared to poles steamed for 14 hours at 245°F. Wood, Erickson, and Dohr compared kiln-dried poles (150°F) to poles steamed at 212, 240, 260, and 270°F for 6 and 15 hours. Data collected from small clears indicate MOR and MOE in static bending and compression parallel to the grain was reduced by a factor of 2 when steamed for 15 hours as compared to 6 hours. Steaming at 270°F for 6 hours reduced MOR and MOE in static bending by 10 and 5 percent, respectively, and 15 percent in compression parallel to the grain.

W. E. Hillis (4) summarized from the seminar on high-temperature drying held in Australia in 1975 that high-temperature drying is a major development in the wood industry and may be used successfully, but its limitations and accurate control must be recognized. He stated that information on time-temperature-moisture effects on the chemistry and fine structure of softwoods and hardwoods in the 110-200°C range is needed.

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Table 1. Differences in Strength Properties of 2-inch Clears in Kiln-drying at 140°F and at Higher Temperatures.

	Drying conditions			
	Kiln	Organic vapors		
Strength property	140°F	190°F	225°F	250°F
Modulus of rupture	1.00	0.95	0.86	0.82
Modulus of elasticity	1.00	1.02	0.97	1.00
Work to proportional limit	1.00	0.98	0.94	0.81
Work to maximum load	1.00	0.83	0.64	0.51
Compression perpendicular to grain	1.00	1.01	1.06	0.89
Side hardness	1.00	0.97	0.96	0.88

Table 2. Differences in Bending Strength of 1-inch Clears in Kiln Drying at 153°F and at Higher Temperatures.

	Drying conditions		
	Kiln		Xylene vapor
Strength property	153°F	202°F	220°F
Modulus of rupture	1.00	0.97	0.93
Modulus of elasticity	1.00	0.99	0.92
Work to maximum load	1.00	0.93	0.87

Table 3. Differences in Strength Properties of 1 1/2-inch Clears in Kiln-Drying at 150°F and Higher Temperatures.

Strength property	150°F	180°F	195°F	215°F	230°F
	Dry bulb temperatures				
Douglas-fir					
Shear, tangential	1.00	0.92	0.88	0.81	0.90
Shear, radial	1.00	0.98	0.90	0.84	1.01
Fiber stress at proportional limit	1.00	1.01	1.01	0.97	0.90
Modulus of rupture	1.00	0.99	0.98	0.89	0.90
Modulus of elasticity	1.00	0.99	1.00	0.95	0.97
Toughness, tangential	1.00	0.90	0.86	0.74	0.76
Toughness, radial	1.00	0.91	0.86	0.75	0.77
Western hemlock					
Shear, tangential	1.00	0.94	0.93	0.88	0.87
Shear, radial	1.00	0.95	1.02	0.97	0.91
Fiber stress at proportional limit	1.00	1.02	1.00	1.05	0.97
Modulus of rupture	1.00	1.02	0.99	0.97	0.89
Modulus of elasticity	1.00	1.02	1.01	1.03	1.03
Toughness, tangential	1.00	0.97	0.95	0.94	0.81
Toughness, radial	1.00	0.97	0.97	0.95	0.85

Table 4. Differences in Bending Strength of 2- by 6-inch Dimension Lumber in Kiln Drying at 170°F and at Higher Temperatures.

Strength property	Dry bulb temperatures		
	170°F	200°F	230°F
Douglas-fir			
Modulus of rupture			
40% SR	1.00	0.93	0.85
60% SR	1.00	0.86	0.79
80% SR	1.00	0.93	0.79
Modulus of elasticity			
40% SR	1.00	0.97	0.98
60% SR	1.00	0.99	1.02
80% SR	1.00	0.98	0.98
Western hemlock			
Modulus of rupture			
40% SR	1.00	0.93	0.90
60% SR	1.00	1.01	0.86
80% SR	1.00	0.94	0.90
Modulus of elasticity			
40% SR	1.00	1.00	1.03
60% SR	1.00	1.03	0.99
80% SR	1.00	1.01	1.01

Table 5. Differences in Tensile Strength of 2- by 6-inch Dimension Lumber in Kiln Drying at 170°F and at Higher Temperatures.

	Dry bulb temperatures		
Tensile strength	170°F	200°F	230°F
Small knot (3/4 to 1 inch)			
Douglas-fir	1.00	0.92	0.89
Western hemlock	1.00	0.95	0.79
Large knot (1-1/4 to 1-1/2 inches)			
Douglas-fir	1.00	0.84	0.78
Western hemlock	1.00	1.01	0.98

Table 6. Differences in Selected Strength Properties in Kiln Drying at 140°F-170°F and at Higher Temperatures.

	Drying temperatures		
Strength properties	140-170°F	195-202°F	215-230°F
Douglas-fir			
Modulus of rupture	1.00	0.95	0.84
Modulus of elasticity	1.00	0.99	0.98
Shear	1.00	0.89	0.89
Tension parallel to grain	1.00	0.88	0.84
Western hemlock			
Modulus of rupture	1.00	0.97	0.90
Modulus of elasticity	1.00	1.01	1.02
Shear	1.00	0.98	0.91
Tension parallel to grain	1.00	0.98	0.89

STRENGTH OF SOUTHERN PINE LUMBER DRIED AT HIGH TEMPERATURES

By Peter Koch

When restraint against warp is applied, grade and value of southern pine studs dried at 240° F is significantly higher than that of matched lumber conventionally dried at temperatures below the boiling point. Experimental evidence has indicated that with 1,000 ft/min air velocity through narrow kiln loads, dimunition of mechanical properties (1 to 4 percent) caused by 240° F, 21-hour drying schedules for log-run, green southern pine 2 by 4's is not of practical significance. Further research is in progress to examine the effects of brief exposure of 1.75-inch-thick southern pine lumber to temperatures in excess of 240° F.

The experimental background and industrial application of high temperature drying for southern pine dimension lumber have been outlined previously. Details of the research are found in the references (Koch 1971; 1972a, b; 1973; 1974a, b; Lemoine and Koch 1971).

It is agreed that extended exposure of southern pine to temperatures above 212° F diminishes some of its mechanical properties. The question is: *How much diminution occurs during the short time required to dry southern pine to 9 or 10 percent moisture content, and is it of practical importance in light of offsetting advantages, e.e., economy of drying and increase in lumber value due to decreased warp?*

To simplify the discussion, I'll concentrate on log-run, green 1.75-inch-thick southern pine exposed for 21 hours to dry- and wet-bulb temperatures of 240° F/160° F in combination with an air velocity of 1,000 ft/min. This schedule is selected because it is in widespread use and, when applied to kiln loads 4 feet wide, will yield an average moisture content of 9 or 10 percent.

Additionally, the discussion concludes with a brief review of data on mechanical properties of southern pine dried at temperatures above 240° F.

Studs Dried at 240° F

In my opinion, mechanical properties of green, log-run, 1.75-inch-thick southern pine lumber dried under restraint in narrow loads for 21 hours at 240° F/160° F with 1,000 ft/min cross-circulation, are not diminished to a practically significant degree that would offset increased lumber value due to control of warp.

The evidence is contained in Koch (1971). This experiment evaluated mechanical properties in edgewise bending of 66-inch lengths of log-run planed studs (1 1/2- by 3 9/16-inch planed dimensions); of the 288 studs broken, half were kiln-dried at 240°F/160°F for 21 hours and half were kiln-dried at temperatures not exceeding 180°F. At test, stud moisture content ranged from 6.1 to 9.6 percent. Moisture content of high-temperature studs averaged 7.36 percent, and that of low-temperature studs was 7.77; at the 0.05 level, these values were not significantly different. All studs averaged 0.51 specific gravity (basis of ovendry volume and weight); specific gravity did not differ significantly by drying schedule.

In addition to the bending test, a pair of clear toughness specimens was evaluated from each of the 288 studs. Specific gravity of these clear specimens averaged 0.52 (volume at test and ovendry weight). Moisture content of the high-temperature specimens was 8.35 percent; that of the low-temperature specimens was 8.78--values that differed significantly at the 0.01 level.

Modulus of elasticity.--The low-temperature studs averaged 1,570,000 psi, and the high-temperature studs averaged 1,541,000 psi in MOE, a diminution of 1.85 percent, which proved nonsignificant (0.05 level) by analysis of variance.

By covariance analysis, with values adjusted to population average moisture content and specific gravity, low-temperature studs averaged 1,591,000 psi in MOE, and high-temperature studs averaged 1,519,000 psi, a decrease of 4.53 percent. This difference was not statistically significant.

Proportional limit.--The low-temperature studs averaged 5,065 psi, and the high-temperature studs averaged 4,850 psi in proportional limit, a diminution of 4.25 percent, which proved nonsignificant (0.05 level) by analysis of variance.

By covariance analysis, with values adjusted to population average moisture content and specific gravity, low-temperature studs averaged 5,056 psi, and the high-temperature studs averaged 4,859 psi in proportional limit. This decrease of 3.90 percent was not statistically significant.

Modulus of rupture.--The low-temperature studs averaged 7,050 psi, and the high-temperature studs averaged 6,750 psi in MOR, a diminution of 4.26 percent, which proved nonsignificant (0.05 level) by analysis of variance.

By covariance analysis, with values adjusted to population average moisture content and specific gravity, low-temperature studs averaged 6,873 psi, and the high-temperature studs averaged 6,934 psi in MOR, an increase of 0.89 percent. This difference was not statistically significant.

Toughness.--The low-temperature clear-wood specimens averaged 192 inch-pounds, and the high-temperature averaged 197 inch-pounds in toughness. This increase of 2.60 percent proved nonsignificant (0.05 level) by analysis of variance.

By covariance analysis, with values adjusted to population average moisture content and specific gravity, low-temperature clear-wood specimens averaged 195.5 inch-pounds, and the high-temperature specimens averaged 192.7 inch-pounds in toughness, a diminution of 1.43 percent. This difference was not statistically significant.

I see no reason to alter the conclusions drawn in the 1971 publication (Koch 1971, p. 24):

> The small size of this test--288 studs in all--perhaps limits the generality of conclusions that may be drawn. The statistical design was sound, however, and so some observations seem warranted.
>
> Reductions in modulus of elasticity, proportional limit, modulus of rupture, and toughness caused by the high-temperature schedule did not prove statistically significant (0.05 level) in this small-scale test; it is probable, though, that large-scale tests would indicate that the 24-hour, high-temperature schedule slightly reduces (1 to 4 percent) major strength properties of log-run 2 by 4's in comparison with schedules that do not exceed 180°F.

Should 240°F schedules be prolonged to 36 or 42 hours--a practice to be deplored--because of overly wide loads, over-thickness lumber, low air velocity, or poor temperature or velocity distribution, then strength diminution will likely be proportionately greater. The solution lies in narrowing the load, thicknessing the lumber, and controlling kiln conditions to the specified levels.

Temperatures Above 240° F

Because the technology of drying lumber at temperatures above 212°F is still evolving, it is useful to review results from experiments in which southern pine was dried at temperatures up to 500°F.

Southern pine lumber 7/16-inch thick and 4, 6, 8, 10, and 12 inches wide dried at varying temperatures.--Koch (1964a,b) dried 120 log-run boards by each of five drying regimes, four of which are germane to this discussion: air drying, drying in a cross-circulating lumber kiln for 72 hours at temperatures not exceeding 186°F (to 4.7 percent M.C.), drying in a 3,500-ft/min jet veneer dryer at 300°F for 56 minutes (to 5.1 percent M.C.), and drying in a 600-ft/min conventional veneer dryer at 300°F for 88 minutes (to 4.4 percent M.C.). All boards were equilibrated together for more than a month to reach about 9 percent M.C., then thicknessed to 1/3-inch, and measured for MOE. Results were as follows:

Process	*Time*	*MOE*	*Specific gravity (ovendry weight and volume at test)*
		psi	
Air dried	3 months	1,720,000	0.52
Dried in lumber dry kiln at 186°F	72 hours	1,660,000	.52
3,500-ft/min, 300°F veneer dryer	56 minutes	1,660,000	.52
600-ft/min, 300°F veneer dryer	88 minutes	1,690,000	.54

Board MOE did not differ significantly by drying treatment, nor did specific gravity. Each average above is for 120 boards.

From these boards, 21-laminae beams were glued in five widths (4, 6, 8, 10, and 12 inches), for a total of five beams made of lumber dried by each procedure. The beams, which averaged 11.8 percent M.C., were then broken; beam MOR, MOE, specific gravity, and moisture content did not vary significantly by drying treatment:

Process	*MOR*	*MOE*	*Specific gravity (ovendry weight and volume)*
	------psi------		
Air dried	9,620	1,670,000	0.53
Dried in lumber dry kiln at 186°F	9,570	1,600,000	.53
3,500-ft/min, 300°F veneer dryer	9,210	1,600,000	.52
600-ft/min, 300°F veneer dryer	10,470	1,680,000	.53

High-strength beams laminated from 1/6-inch southern pine veneer dried at 400°F.--Koch and Woodson (1968) demonstrated that high-strength beams can be made of thick southern pine veneers dried in a 400°F jet dryer.

Average observed dynamic MOE for the 8,280 rotary-peeled veneers from which beam laminae were drawn was 1,810,000 psi at 7.6 percent M.C.; specific gravity (ovendry weight and volume at 7.6 percent M.C.) was 0.536. By regression relationship established in the experiment, average static MOE for these log-run strips (at 7.6 percent M.C.) was calculated at 1,690,000 psi. This is 100,000 psi less than the Wood Handbook's species-average value for MOE of clear loblolly pine at 12 percent M.C. (U. S. Forest Products Laboratory 1974).

Twenty 18.42-inch-deep beams were laminated from these veneers placed according to elastic moduli (those with greatest elastic moduli placed outermost and graded inwardly) and butt-jointed; MOE (corrected for shear deflection) of the beams averaged 2,110,000 psi, and MOR averaged 9,020 psi. The average beam specific gravity (volume at 12.2 percent M.C. and ovendry weight) was 0.59.

These data indicate that short exposure of 1/6-inch veneers to 400°F temperature does not damage their strength in any practically significant way.

Rotary-peeled veneer 0.132-inch thick dried at 500°F.--Suchsland and Stevens (1968) dried rotary-peeled, 0.132-inch thick southern pine veneer in an oven held at 500°F while they measured surface temperature with a radiation thermometer. Plywood was made from the veneer, and shear strength measured. They concluded that it was feasible to dry at 500°F if drying was terminated before the veneer surface reached the temperature of the drying air. Their data showed that veneer moisture content fell to about 10 percent before its surface temperature exceeded 250°F; when zero M.C. was approached, surface temperature was about 350°F.

Thus, a continuous dryer for southern pine lumber could be constructed with zone control of temperatures manipulated to avoid surface temperatures deleterious to wood mechanical properties.

Conclusions

From all these data, I conclude that southern pine lumber can be dried by short exposure to temperatures up to 240°F without diminishing mechanical properties by an amount that has practical significance. How brief exposure to temperatures above 240°F affect 1.75-inch-thick southern pine lumber is still under investigation.

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HIGH-TEMPERATURE DRYING EFFECT ON THE BENDING STRENGTH OF SPRUCE-PINE-FIR JOISTS

by

D.R. Huffman

INTRODUCTION

For some softwood species, high-temperature drying promises not only shorter drying time but often reduced degrade compared to conventional schedules. Few studies have been conducted specifically to assess the effect of drying schedule on the strength of full-dimension construction lumber. Consequently some mills have been reluctant to adopt high-temperature drying, believing that substantial strength reductions might result.

A recent study on the high-temperature drying of eastern spruce – jack pine – balsam fir (1) provided a general indication of schedule effect on strength because the study was concluded with static bending tests of the full-dimension joists. A statistical analysis of the relationship between bending strength and drying schedule has been completed (2); this paper briefly describes the study and gives an estimate of the effect of high-temperature drying on average bending strength of the three species. Since sample selection was based solely on criteria for degrade evaluation and drying time determination, the sample size in the lower part of the strength range was inadequate to determine the quantitative effect of high-temperature drying on the basic design stresses for this species group.

PROCEDURE

The test material consisted of mill-run proportions of Select Structural and No. 1 (National Lumber Grading Authority, 1970) nominal 2 x 6-inch (50 mm x 150 mm) joists 8 feet (2.4 m) in length. Equal numbers of eastern spruce, jack pine and balsam fir joists were kiln dried to final average moisture contents (MC) of 12 to 14 percent. (The spruce and pine came from Northern Ontario; the fir from the Ottawa valley). Two schedules were employed: a conventional schedule with dry bulb temperatures of 150^0 to 180^0F (66^0 to 82^0C) and a high-temperature schedule with a constant dry bulb temperature of 240^0F (116^0C).

The variability in bending strength determined from in-grade tests is substantial, and detection of a schedule effect requires a large number of replications when using a simple comparison of means. In order to reduce the

unaccounted-for variation, an indication of inherent strength was obtained from a static bending test of each joist before drying. The joists were tested on edge with third-point loading, a span of 90 inches (2.3 m) and a loading rate of 0.275 inch (7 mm) per minute. Sufficient load was applied to establish a load-deflection curve for calculation of green Modulus of Elasticity (MOE), but without approaching the proportional limit.

After drying, the joists were stored under controlled conditions of 70^0F (21^0C) and 65 percent relative humidity for 3 to 7 weeks before being surfaced, regraded, and tested to destruction. Dry MOE and Modulus of Rupture (MOR) were calculated and adjusted to a common MC of 12 percent. MC's ranged from about 8 to 17 percent with the average of all conventionally-dried joists being 12.6 percent and of high-temperature-dried joists, 12.2 percent. The standard deviations were 1.2 and 1.8 percent respectively. Data from all joists which graded No. 2 or better after drying were retained for linear regression analysis, with dry values regressed on green MOE for each schedule. Regression lines were calculated for all data combined and for data from each species separately. In each of these four cases data from the conventional schedule and data from the high-temperature schedule were compared by homogeneity-of-regression tests to determine if a schedule effect was present; if the initial test showed significance, a second test was carried out to compare regression line slopes. To complete the examination of schedule effect, comparisons were made of the regression of dry MOR on dry MOE.

RESULTS

Modulus of Elasticity

With data from all species combined, comparison of the regression line for high-temperature drying with that for conventional drying yielded an F-value of 1.59 -- not significant at the 0.05 level (Table 1). Calculation of dry MOE's from the regression equations using the overall average green MOE of 1.16×10^6 psi (8.03 GPa) gave 1.47×10^6 psi (10.11 GPa) for conventionally-dried joists and 1.45×10^6 psi (9.98 GPa) for high-temperature-dried material, a reduction of only 1.3 percent (Table 2).

On an individual species basis, effect of schedule on MOE was non-significant in eastern spruce and in balsam fir as the predicted average reductions resulting from high-temperature drying were only 1.1 percent. For jack pine schedule effect was significant at the 0.05 level with an F-value of 3.86. For the average green MOE of jack pine, 1.15×10^6 psi

(7.92 GPa) predicted dry MOE's were 1.47 x 10^6 psi (10.15 GPa) and 1.44 x 10^6 psi (9.92 GPa) for conventional and high-temperature schedules respectively, a reduction of 2.2 percent.

Modulus of Rupture

For data from all species combined the homogeneity-of-regression test indicated a strong schedule effect, significant at the 0.01 level (Table 1). Although the regression lines diverge slightly (Figure 1), the difference in slopes was not statistically significant. The 95 percent confidence bands for the regression lines indicate that in the lower portion of the strength distribution a statistically significant difference did not occur. At the overall average green MOE, the predicted dry MOR for conventionally-dried joists was 6.44 x 10^3 psi (44.43 MPa) compared to 5.69 x 10^3 psi (39.22 MPa) for high-temperature-dried material, a reduction of 11.7 percent (Table 2).

Results were similar when each species was considered individually, with a highly significant schedule effect but no significant difference between regression line slopes (Table 1). Dry MOR's predicted from the regression equations at the average green MOE of each species showed reductions of 13.5 percent in jack pine, 11.0 percent in eastern spruce and 10.2 percent in balsam fir (Table 2).

Relationship of Dry MOR to Dry MOE

The relationship of dry MOR to dry MOE for conventionally-dried joists was significantly different from that for high-temperature-dried joists, because large reductions in MOR occurred with little or no reduction in MOE. At the average dry MOE for the species group, the predicted MOR values were 6.39 x 10^3 psi (44.08 MPa) and 5.83 x 10^3 psi (40.20 MPa) respectively, an average difference of 8.8 percent (Table 2). Also, a comparison of the regression slopes gave an F of 3.39, significant at the 0.05 level. With the high-temperature regression line having a lower slope, the predicted difference increased from about 5 percent to over 10 percent in the range of dry MOE's encountered.

When the three species were considered individually, the regression lines predicted significantly lower MOR values for high-temperature dried joists than for conventionally dried joists. At the species average dry MOE, reductions were 8.0 percent in spruce, 10.7 percent in jack pine and 8.8 percent in balsam fir. In spruce and fir there was no significant difference between regression line slopes but in jack pine the difference was significant at the 0.05 level, with the

predicted difference increasing as dry MOE increased.

SUMMARY AND DISCUSSION

Static bending tests were carried out on full-dimension kiln-dried joists of eastern spruce – jack pine – balsam fir. Green MOE of each piece was determined before drying to provide an indicator of inherent strength and thereby enable comparison of similar joists, dried under different schedules. Linear regression analysis was employed with dry values of MOR and MOE regressed on green MOE, and the regression lines compared by statistical tests.

These analyses established that the average MOR of high-temperature-dried joists was significantly lower than that of conventionally dried joists. For a mixture containing equal volumes of the three species and mill-run proportions of Select Structural and Number 1, an average reduction of 11.7 percent was predicted by the regression lines. The average reduction of 1.3 percent predicted for MOE was not statistically significant at the 0.05 level.

Analyses for individual species indicated that jack pine suffered the greatest reductions, with a statistically significant lower average MOR, 13.5 percent, and average MOE, 2.2 percent. Eastern spruce had a non-significant reduction in average MOE of 1.1 percent and a statistically significant reduction in average MOR of 11.0 percent. Similarly, in balsam fir the average MOE reduction of 1.1 percent was non-significant but the reduction in average MOR of 10.2 percent was significant.

Linear regression lines predicting dry MOR from dry MOE were significantly different for conventional and high-temperature-dried joists. Therefore in machine grading the use of a relationship obtained from tests on conventionally dried joists to predict MOR of high-temperature-dried joists would lead to overestimation, with the magnitude of the error increasing with joist quality for a mixture containing the three species.

In this study the criteria for specimen selection were based on consideration of drying time and degrade; therefore the number of joists representing the lower end of the strength distribution was not adequate to show a statistically significant difference between high-temperature and conventionally-dried material. Therefore, it is not advisable to form conclusions as to the effect of high-temperature drying on design stresses other than to note that not one

high-temperature-dried joist failed at a stress below the present designed-for stress (allowable unit stress times safety factor) for its grade.

Clearly there is a need for additional study of this species group to determine the distributions of strength properties of full-dimension construction lumber as affected by species, grade, drying conditions and physical characteristics.

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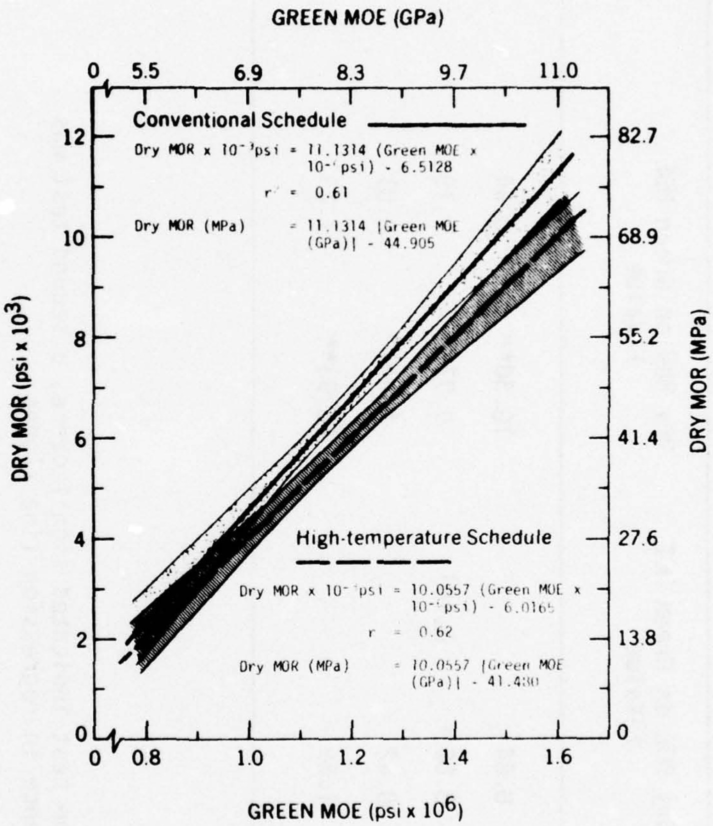

Figure 1. Linear Regressions and 95% Confidence bands for Each Line as a Whole for Dry Modulus of Rupture on Green Modulus of Elasticity (All Species Combined).

Table 1. HOMOGENEITY OF REGRESSION COMPARISON OF SCHEDULE EFFECT

	Dry MOE on Green MOE F-Value		Dry MOR on Green MOE F-Value		Dry MOR on Dry MOE F-Value	
Eastern Spruce	0.84		10.30**	0.64	4.29*	0.43
Jack Pine	3.86*	0.10[1]	9.07**	1.19	6.49**	3.08*
Balsam Fir	0.42		5.46**	0.01	6.14**	1.01
All Species Combined	1.59		16.93**	1.39	13.70**	3.39*

* Significant at 0.05 level

** Significant at 0.01 level

1 Where homogeneity-of-regression test indicated significance, a second test was performed to check for difference in regression line slopes.

Table 2. EFFECT OF DRYING SCHEDULE ON MODULUS OF ELASTICITY AND MODULUS OF RUPTURE

	Units and Schedule	Eastern Spruce	Jack Pine	Balsam Fir	All Species Combined
Green MOE[1]	psi x 10^6	1.25	1.15	1.09	1.16
Dry MOE (predicted from regression on Dry MOE on Green MOE at average Green MOE)	Conventional[3] High-temp.[3]	1.65 1.63	1.47 1.44	1.27 1.26	1.47 1.45
Reduction due to H.T.[2](%)		1.1±1.8[4]	2.2±2.1	1.1±2.4	1.3±1.4
Dry MOR (predicted from regression of Dry MOR on Green MOE at average Green MOE)	Conventional High-temp. psi x 10^3	7.68 6.83	7.01 6.06	4.63 4.16	6.44 5.69
Reduction due to H.T. (%)		11.0±4.9	13.5±6.5	10.2±6.2	11.7±4.1
Dry MOE	psi x 10^6	1.63	1.46	1.26	1.45
Dry MOR (predicted from regression of Dry MOR on Dry MOE at average Dry MOE)	Conventional High-temp. psi x 10^3	7.74 7.11	6.85 6.12	4.58 4.18	6.39 5.83
Reduction due to H.T. (%)		8.0±5.3	10.7±6.7	8.8±5.3	8.8±3.6

1 Average for all joists for both schedules
2 High Temperature
3 Sample size for Conventional Schedule, for Sp-Pj-bF, was 57, 59 and 58 respectively; Sample size for High-temp. Schedule, for Sp-Pj-bF, was 57, 58 and 54 respectively.
4 A 95 percent confidence interval estimate for the difference between mean regressed values of y at a single point ($\bar{X}$)

COMMENTS ON HIGH-TEMPERATURE DRYING OF CONSTRUCTION LUMBER

by

Lumber Seasoning Unit of EFPL, Ottawa, Canada

Experiments on H.T. drying were conducted at the EFPL during the early 1950's and the initial results were published in 1955, describing the drying behavior of white spruce subjected to a constant temperature of 240°F D.B., 200°F W.B. and various air velocities. Evaluation of various drying parameters continued and in 1957 tentative drying schedules were published for six eastern softwoods.

In 1962, emphasis was placed on the H.T. drying of hardwoods. This included some basic work on stress-strain relationships and low-temperature pre-drying. Further research on softwoods was not undertaken until 1966, at which time a study was initiated to examine the effect of sawing pattern and H.T. drying on degrade in plantation-grown red pine. This was followed by a continuing program on the drying of construction lumber: spruce, jack pine, balsam fir and aspen. In each case the objectives were to obtain a substantial reduction in drying time with no increase in degrade. No attempt was specifically made to evaluate the economics of H.T. drying, or to determine its effect on strength properties.

On a commercial scale, mills in eastern Canada have been slow to accept H.T. drying as an alternative to conventional kiln drying. However, on the basis of drying time and lumber quality alone, a few progressive mills have decided in favor of H.T. drying facilities, while a number are operating over a range from elevated conventional to high temperature depending on fluctuations in available energy.

Effect on Strength

EFPL studies on H.T. drying were designed to determine the effect of schedule on drying time and degrade; they were not designed to determine the effect of drying temperature on strength. The timber engineering division has not examined the possibility of a strength reduction due to H.T. drying. Therefore, conclusive answers are not available in the EFPL as to whether in-grade strength is significantly affected. Recent seasoning studies have included rudimentary strength testing (MOE and MOR) of construction lumber, fully realizing that the results would serve only as a general indication.

Two separate questions arise concerning drying schedule effect on mechanical properties:

1) To what extent is strength reduced?

and

2) Of what importance is a strength reduction in relation to structural application?

Data from tests on 2" x 6" x 8' joists of the Sp-Pine-Fir species group indicated that MOE was not significantly reduced by high-temperature drying. Average values of MOR were significantly lower for high-temperature-dried joists than for conventionally-dried joists; the magnitude of the strength reduction in any given joist was extremely variable, depending on species, type (pith or non-pith) and grade. Average reductions (when corrected to a common final MC) ranged from 10 to 13%, but at the lower end of the strength distribution sample sizes were not adequate to show a statistically significant difference.

In the Sp-Pine-Fir group design stresses reflect the strength of balsam fir, which is the weakest species. Since both jack pine and eastern spruce are substantially stronger than the fir, a 5 to 10% reduction in MOR in these species will not affect the safety factor for the species group. The fir does not respond well to high-temperature drying because of the presence of wetwood and it often develops severe drying defects which usually cause a drop in grade. Since the strength reduction from H.T. drying is accompanied by grade drop, the MOR of the degraded material is not significantly lower than that of non-degraded conventionally-dried lumber of the lower grade. Although we are convinced that the ultimate total load at failure for a large sample of Sp-Pine-Fir construction lumber would be slightly lower if a high-temperature schedule were used, we do not expect that the present 24-hour, 240°F schedules would produce construction lumber that is unsafe under present design stresses for this species group.

Future Program With Respect to H.T. Drying

Work in the near future will involve studies on drying efficiency, including schedule development and modification to achieve optimum energy-time input. This will involve a comparative cost evaluation of energy sources, namely steam, gas and electricity, and possible combinations of wood residue. In anticipation of this work the EFPL acquired a new 5 Mbf experimental kiln with steam, gas and electrical heating systems.

Our work on optimizing drying efficiency will also give us the opportunity to further evaluate the effect of initial steaming and final conditioning with respect to lumber quality, drying rate and energy consumption for H.T. drying.

At present there are no plans to examine more severe H.T. drying schedules since this would create problems in kiln design, equipment and heating capacity. Also, the present 24-hour schedules for construction lumber appear well suited to a normal work schedule. On the other hand we are in full support of developing a continuous flow drier, but it is not our intention to undertake any work in this respect.

SUGGESTIONS FOR FUTURE RESEARCH RE STRENGTH PROPERTIES OF HIGH-TEMPERATURE-DRIED CONSTRUCTION LUMBER

Wood is the only major structural material that is not man-made and its performance is governed by its extremely wide variation in strength properties. Safe structural design can be obtained in two ways: by either gross overdesign or by precise determination of actual strength properties of each piece and segregation of material into groups with uniform performance characteristics. In the past, wood was abundant and very inexpensive, and the overdesign route was followed with, in some cases, only primeval attempts to categorize and segregate according to performance (amply illustrated by the Sp-Pine-Fir species group where, for example, No. 2 black spruce can be twice as strong as SS balsam fir). However, in recent years society has expressed considerable criticism of design practices which result in extravagant use of natural resources. It is to be expected that we will not be able to continue overdesign simply to avoid the responsibility of obtaining the information required to accurately design for safe *and* efficient utilization.

The introduction of a new drying system requires not just the determination of a precise factor to characterize any reduction of strength due to the new system, but also a consideration of whether the addition of this factor to the formula of uncertain design is justified, i.e. answer the question of whether or not acceptable performance is obtained without an additional adjustment factor. Unfortunately, the information required to precisely define the limits of acceptable performance is not available for full-dimension construction lumber. At present there is uncertainty about the duration of load effect; the form of strength distributions and the allowable failure level have been questioned; the effect of MC has not been fully established; and there is considerable evidence that visual stress grades relate poorly to strength.

Based on the present state of uncertainty in design we suggest that the following work is required:

1) Data must be obtained on the mechanical properties of full-dimension construction lumber, including strength distributions as influenced by species, regional variation, grade, type (e.g. pith or non-pith), processing, and physical characteristics. This information is required so that sample selection for schedule-effect investigations can be limited to critical areas of the species-group population.

2) Data must be acquired which will accurately relate performance of in-grade structural lumber to measurable strength properties or physical characteristics. This would include consideration of duration of load (and effect of drying and moisture cycling under load), effect of MC, effect of member dimensions, effect of grade, etc. These data are required to enable calculation of a dollar value cost which would result from specific changes in mechanical properties, and allow inclusion of strength in economic analyses of conversion and processing operations, including drying.

3) An examination of the effect of drying schedule (including temperature, humidity, conditioning treatments, etc.) on the critical strength properties of full-dimension lumber selected in the critical region of the population strength distribution. These data are required to accurately relate schedule to probabilistic failure rates in service.

4) Basic research is required to explore the relationship between drying environment and strength properties of wood. This information would provide the tools for schedule modification to minimize strength losses or to alter specific mechanical properties for defined structural uses.

In order to dramatize the complexity of the problem we provide the following example of a simple request from a lumber seasoning researcher:

In our energy evaluation program we will be drying softwood construction lumber of the Sp-Pine-Fir species group under both conventional and high-temperature schedules. It is possible to measure a strength property in order to determine effect of high-temperature drying on the safety of construction lumber; however, in order to justify the expenditure of time and money on strength testing, we *must be certain* that the material being tested represents the area of structural design which *is most critical.*

Therefore we require documented answers to the following questions:

1) Which species (in the group) is critical?

2) What area of growth (region, site etc.)?

3) What grade?

4) What type (pith, non-pith, sap, heart etc.) and what physical characteristics (rate of growth, density, resin content, etc.)?

5) What area of the strength distribution should be measured and what measurements of the green material should be taken to allow efficient covariate analysis?

6) Which strength property should be measured?

7) What should sample dimensions be?

8) What test procedure should be followed?

9) To what final MC should the lumber be dried?

10) What equalization procedure should be followed prior to testing?

11) What processing should be applied prior to test and finally,

12) How large a change in the strength property measured should be considered significant at what probability level and, consequently, what sample size is required?

COMPARISON OF MECHANICAL PROPERTIES OF DOUGLAS-FIR AND SOUTHERN PINE LUMBER DRIED BY CRT, HIGH TEMPERATURE, AND CONVENTIONAL SCHEDULES

By G. L. Comstock

BACKGROUND

Weyerhaeuser for several years has been implementing the CRT (Continuously Rising Temperature) process in its drying operations throughout the U.S. and Canada. One of the early concerns raised about CRT was the possibility of the elevated temperatures causing reductions in strength properties as Kozlik had shown occurs for Douglas fir during high temperature drying. The question was raised since CRT often involves the use of temperatures well over 212°F toward the end of the cycle. Temperatures early in the cycle are normally lower than those used in conventional schedules.

These two studies reported here on Douglas-fir and southern pine were originated to test the influence of both high temperature and CRT drying on mechanical properties in comparison to conventional drying procedures.

EXPERIMENTAL PROCEDURE - DOUGLAS-FIR

Drying was done by 3 methods, a conventional schedule, a high temperature schedule and a CRT schedule. Details of the schedule, and drying times are as follows:

	DB(°F)	WB(°F)	Drying Time(Hrs)
Conventional	170	150	24
	170	140	24
	170	120	22
	170	164	2
			72 Total
High Temperature	210	190	4
	230	190	20
			24 Total
CRT	120 Start	75 Start	
	250 Final	170 Final	24 Total

Material selected for the study consisted of nominal 2x6-inch by 14 foot Douglas-fir dimension. Approximately 480 pieces of rough green material were graded by a qualified company grader. The material consisted of 168 pieces of Select, 168 pieces of Construction and 144 pieces of Standard 2x6 dimension.

The MOE value of each green piece was determined nondestructively using the "E" computer. These MOE values were then arranged in ascending order for each grade. The three specimens with the lowest MOE values were randomly assigned to each of the three drying schedules. Then the unseasoned specimens with the next lowest values for MOE were assigned randomly, and so on until all pieces within each grade classification had been assigned to one of the three schedules. Thus the mean MOE values with each grade classification were nearly identical for each drying schedule.

The specimens were then interspersed in three kiln charges and dried to 15 percent moisture content. After drying, all test material was stored in the rough dry shed approximately 8 months for equalizing. MOE values were determined using the "E" computer. The samples were tested to destruction, as a joist, with third point loading using a span/depth ratio of 17:1. MOR values were calculated for each specimen and adjusted for a moisture content of 12%.

EXPERIMENTAL PROCEDURE - SOUTHERN PINE

The drying aspects of this study were conducted at Wright City, Oklahoma. Three drying methods were compared, CRT, high temperature and progressive. The approximate schedules and drying times are as shown below:

CRT	- *140°F-250°F DB*	*100-180°F WB*	31 hrs.
High Temp.	- 235°F DB	180°F WB	34 hrs.
Progressive	- 200-230°F DB	170°F WB	72 hrs.

Test lumber was all 8' 2x4's from small logs produced through the chip-n-saws. Sixty (60) pieces each of #1 dense, #2 dense and #2 medium grain were dried by each of the three drying methods. A total of 540 pieces were used in the study. To ensure homogeneity between lumber dried by the different methods the procedure used was to select (using a Wright City grader) 180 pieces of each of the three grades from normal mill production. These 180 pieces were then randomly assigned to one of the three drying methods. This procedure gave relatively close matching of test stock assigned to the three drying methods. The lumber was dried to average moisture content levels of about 14%. After drying the lumber was surfaced and shipped to Longview, Washington for further testing. In Longview it was stored in the Testing Laboratory on stickers for about 2 months prior to testing and allowed to equilibrate. The laboratory is conditioned at 70°F, 50% relative humidity. The lumber equilibrated under these conditions at between 10 and 11 percent moisture content. Crook, bow and twist of each piece was measured.

Each piece was mechanically tested to destruction as a joist using ASTM Test D-198. Data obtained were MOE, MOR, fiber stress at proportional limit, fiber stress at failure and whole piece toughness.

MECHANICAL PROPERTIES COMPARISON

Douglas fir - The comparison of lumber dried by the three methods is shown in Table I. No significant differences in MOE were found, but the high temperature dried lumber had significantly lower MOR values in every grade category. CRT dried lumber had MOR values equivalent to conventionally dried lumber even though the drying temperature near the end of the kiln cycle reached 250°F, 20°Γ above that of the high temperature schedule. One interpretation is that the damage to the wood during high temperature drying takes place early in the drying cycle when the wood is quite wet and conditions are favorable for hydrolysis.

Southern pine - These data are shown in Table II. Most values of MOE and MOR are very similar for a given grade regardless of drying method, but some differences are statistically significant. CRT and conventional schedules gave essentially identical results. High temperature drying produced a significantly lower MOR in the #1D grade than CRT or conventional. It also produced a significantly lower MOE than CRT although the difference amounts to only about 3 percent.

A comparison of these results to those obtained by Kozlik on Douglas fir and Koch on southern pine are shown in Table III. MOE and MOR values for high temperature dried and CRT dried lumber are shown as a percentage of the value observed on conventionally dried lumber.

The results on high temperature dried lumber are remarkably consistent. They show little change of MOE in any case. MOR was 15% and 20% lower for Douglas-fir and 4% lower for southern pine. All values for CRT are within ± 2% of conventionally dried lumber.

CONCLUSIONS

- High temperature drying schedules can result in significant reductions in MOR of Douglas fir and may result in slight reductions in MOR of southern pine.
- CRT drying of both Douglas fir and southern pine produced MOE and MOR equivalent to that obtained by conventional kiln schedules.
- High temperatures per se do not necessarily damage lumber, since the CRT schedules use temperatures up to 250°F at the end of the kiln cycle.

RECOMMENDATIONS

- Studies be undertaken to determine the influence of varying combinations of temperature, time and moisture content on mechanical properties to determine when in the drying cycle damage occurs and the extent.
- A clear distinction be drawn between CRT and high temperature schedules in considering the influence of drying schedules on mechanical properties.
- Data be gathered on energy consumption, degrade and other drying costs in assessing the merits of various drying procedures.

TABLE 1

COMPARISON OF MOE & MOR VALUES FOR DOUGLAS-FIR

DRYING METHOD	LUMBER GRADE	SAMPLE SIZE	MOE $X 10^6$	MOR
CONVENTIONAL	SELECT	56	2.29	9537
	CONST.	56	1.99	7713
	STD.	48	1.85	6702
	AVG.		2.04	7984
HIGH TEMPERATURE	SELECT	56	2.22	8283*
	CONST.	56	1.91	6607*
	STD.	47	1.76	5504*
	AVG.		1.96	6798*
CRT	SELECT	56	2.19	9770
	CONST.	56	2.04	7214
	STD.	48	1.77	6617
	AVG.		2.00	7867

* DESIGNATES DIFFERENT FROM CONVENTIONAL SCHEDULE VALUES AT THE 95% CONFIDENCE LEVEL

TABLE 2

COMPARISON OF MOE AND MOR VALUES FOR SOUTHERN PINE

DRYING METHOD	LUMBER GRADE	SAMPLE SIZE	MOE X 10^6	MOR
CONVENTIONAL	#1D	60	1.65	9621
	#2D	60	1.52	6982
	#2MG	60	1.22	5954
			1.47	7534
HIGH TEMPERATURE	#1D	59	1.61	8701*
	#2D	59	1.48	6986
	#2MG	61	1.20	6052
			1.43	7233
CRT	#1D	60	1.68	9441**
	#2D	61	1.56**	6946
	#2MG	58	1.26	6278
			1.50**	7555

* DESIGNATES DIFFERENT FROM CONVENTIONAL SCHEDULE VALUES AT THE 95% CONFIDENCE LEVEL

** DESIGNATES DIFFERENT FROM HIGH TEMPERATURE DRYING AT THE 95% CONFIDENCE LEVEL

TABLE 3

MOE & MOR VALUES EXPRESSED AS A PERCENTAGE OF THE VALUES OBTAINED FOR LUMBER DRIED BY CONVENTIONAL SCHEDULES

	MODULUS OF ELASTICITY				MODULUS OF RUPTURE			
	DOUGLAS FIR		SOUTHERN PINE		DOUGLAS FIR		SOUTHERN PINE	
DRYING METHOD	THIS STUDY	KOZLIK[1]	THIS STUDY	KOCH[2]	THIS STUDY	KOZLIK[1]	THIS STUDY	KOCH[2]
HIGH TEMPERATURE	96%	100%	97%	98%	85%	80%	96%	96%
CRT	98%	-	102%	-	99%	-	100%	-

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COMPARISON OF SOUTHERN PINE WARP AND GRADE LOSS

WITH ORT, HIGH TEMPERATURE, AND CONVENTIONAL SCHEDULES

By G. L. Comstock

The primary motivation for use of faster drying schedules has traditionally been the lowering of direct drying cost, especially capital related costs and energy. Another major concern which is sometimes overlooked is the grade or value recovery of lumber. In fact, our data, especially on southern pine have shown value differences to be the key factor in deciding what drying procedure to use. Dollar comparison of lumber value resulting from high temperature and conventional schedules have indicated that both CRT and high temperature schedules give significantly higher value than the conventional schedules and CRT gives a significantly higher value than high temperature.

Visually the difference appeared to be due to differences in the amount of warp. To help clarify what the differences are and further test their significance, the southern pine 2x4's used in the strength comparison were all measured for warp. Measurements were made after equilibration at 10-11% moisture content in the lab and just prior to testing. These data are shown in Tables 4 and 5.

From Table 4 it is clear that CRT resulted in significantly less crook and twist than either high temperature or conventional drying and significantly less bow than conventional drying.

Table 5 shows the percent of pieces meeting the various warp requirements for grades #1, 2 and 3 for each category separately and finally all warp. From these data it is apparent that highest grade recovery would be with CRT followed by high temperature with the conventional schedule having the lowest grade recovery. This is consistent with other studies of grade and yield on southern pine. It is clear from Table 5 that the major degrading warp is crook. Thus efforts aimed at higher grade should be keyed on reducing crook.

Table 4 Warp in 8' 2x4's Dried by 3 Methods

GROUP	CRT			HIGH TEMPERATURE			PROGRESSIVE		
	Bow (in)	Crook (in)	Twist (in)	Bow (in)	Crook (in)	Twist (in)	Bow (in)	Crook (in)	Twist (in)
Green Grade									
#1	0.202	0.152	.078	0.242	0.155	.106*	0.265*	0.206*	.084
#2	0.184	.133	.094	0.186	0.183	.139*	.189	.172	.114*
#2M	0.252	.209	.108	.272	.266*	.186*	.286	.244	.184*
Avg	.212	0.165	.094	.233	.201*	.144*	.246*	.207*	.127*
95% Conf. Lim. on Mean									
Upper	.242	.194	.103	.263	.231	.154	.286	.247	.140
Lower	.183	.136	.084	.204	.172	.135	.206	.167	.114

* Significantly greater than CRT @ 95% confidence level

Table 5 Percent of test pieces meeting warp requirements for different grades for 8' - 2x4's dried by CRT high temperature and progressive drying methods.[1]

Drying Method	Warp Grade	Percent of Pieces Meeting Grade Requirements for Bow	Crook	Twist	All Warp
CRT	#1 & S	92.1	81.4	97.2	75.7
	#2	97.7	91.0	98.9	89.8
	#3	99.4	94.9	100.0	94.9
High Temp	#1&S	90.1	79.7	94.4	71.2
	#2	98.9	92.1	98.3	89.8
	#3	99.4	93.8	100.0	93.2
Progressive	#1&S	86.4	75.6	95.5	68.2
	#2	94.9	86.4	97.7	83.5
	#3	97.2	90.9	99.4	89.2

1 Values shown are for all three green grades, a total of 179 or 180 pieces for each drying method.

EFFECT OF HIGH-TEMPERATURE KILN DRYING ON LUMBER PROPERTIES

by J.F.G. Mackay

Most of the commercial species in Western Canada have been investigated at the Western Forest Products Laboratory in regard to the effect of high temperature drying on quality and strength properties. However the extent of these studies is limited, and the sum of all the research findings that this laboratory has could not be considered to be a comprehensive study on the relationship between drying temperatures and properties. For example, some of the most carefully designed studies were with small clear specimens only, rather than with full-size members. Where full-size members have been tested the main emphasis was directed to kiln schedule development, and only as a later consideration were measurements made of strength properties. Sampling procedures in these instances were likely inadequate for definite conclusions to be drawn.

In some instances some of the studies involved temperature which although higher than 212°F, did not reach 240°F, therefore some of the conclusions reached earlier may not be reliable if we are now to be concerned with higher drying temperatures.

Data on strength properties are available from studies carried out by M. Salamon on four Western softwood species. A summation for each species is shown in Tables 1-6.

Kiln-drying studies with *Abies lasiocarpa*, Alpine fir indicated that schedules with a dry-bulb temperature to 240°F caused internal checking (Salamon 1975).

We recently collected data on the effect of high-temperature drying on strength properties of two poplar species, *Populus tremuloides* trembling aspen and *P. balsamifera* balsam poplar (Mackay 1974). Although these are hardwoods, dimension lumber sawn from them is graded under softwood grading rules. The comparison that we have is between part of a shipment of studs which were dried at 250°F at the laboratory, and similar material dried at 180°F at the supplying mill. Table 7 summarizes the findings. One consistent feature although not statistically proven, was that the reductions in MOR were least in the highest grade which was select structural, and greater in the lower grades. This point deserves greater attention when future work is planned. High temperature drying to 240°F and 250°F has been found to cause internal checking in trembling aspen. However qualified grade inspectors say that internal checks can be tolerated because they are not visible to the visual grader.

No other data are available from this laboratory but the Forest Products Laboratory in Melbourne has data which are relevant in these discussions. First, drying 2 by 4 studs of Radiata pine in a conventional batch kiln at a temperature of 240°F for 24 hours caused no reduction in MOE (Mackay 1971). Second, studs dried at 360°F for 3 1/2 hours in a continuous-feed dryer showed no loss in MOE or maximum crushing strength compared to matched material dried at up to 195°F for 54 hours (Fricke 1975). This raises an important point that strength is perhaps unlikely to be affected by drying a permeable, easy to dry species at temperatures as high as 360°F in view of the lower internal board temperatures resulting

from increased evaporation rates and the extremely brief time of exposure.

The time of exposure to high temperatures is a factor which has long been recognized and measured in studies of thermal degradation and acid hydrolysis of wood and wood constituents. Possibly due to difficulties involved in measuring internal board moisture contents and temperatures, there are few data on the effect of the time of exposure at given high temperatures on the strength of dimension lumber.

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TABLE 1

Douglas-fir

Strength property	Drying Condition		
	Conventional (170°)	High (218°F)	Sup. Steam (225°F)
FS at PL	1.00	0.93	0.90
MOR	1.00	0.87	0.87
MOE	1.00	0.92	0.95
MCS	1.00	0.92	0.89

TABLE 2

Western Hemlock (1)

Strength property	Drying Condition		
	Conventional (185°F)	Low-High (230°F)	High (225°F)
FS at PL	1.00	1.12	1.04
MOR	1.00	1.10	1.04
MOE	1.00	1.08	1.02
MCS	1.00	1.11	1.01

TABLE 3

Western Hemlock (2)

Strength property	Drying Condition		
	Conventional (185°F)	Low-High (230°F)	High (225°F)
FS at PL	1.00	0.97	0.74
MOR	1.00	1.04	0.73
MOE	1.00	1.05	0.59
MCS	1.00	1.04	1.02

All Values shown are relative to Conventional

Source: Salamon 1966

TABLE 4

Western White Spruce

Strength property	Drying Condition				
	Conventional (200°F)	Low-High (232°F)	Low-High (265°F)	High (232°F)	Sup. Steam (230°F)
MOR	1.00	1.01	0.96	1.00	1.02
MOE	1.00	1.02	0.99	0.96	1.00
MCS	1.00	1.00	0.99	0.99	0.97

Values shown are relative to Conventional

Source: Salamon 1973

TABLE 5

Western Red Cedar (1)

Strength property	Drying Condition		
	Conventional (190°F)	Low-High (215°F)	Low-High (225°F)
FS at PL	1.00	0.91*	0.89*
MOR	1.00	0.95*	0.97*
MOE	1.00	1.04	1.02
MCS	1.00	0.97	0.99

Values shown are relative to Conventional

* Significantly different (5% level) from Conventional

Source: Salamon and Hejjas 1971.

TABLE 6

Western Red Cedar (2)

Strength property	Drying Condition	
	Conventional (185°F)	Low-High (230°F)
FS at PL	1.00	1.01
MOR	1.00	1.01
MOE	1.00	1.00
MCS	1.00	1.03

Values shown are relative to Conventional

Source: Salamon and Hejjas 1971

TABLE 7

Northern Aspen

Strength property	Drying Condition and Species			
	Trembling aspen		Balsam poplar	
	Conventional (180°F)	High (250°F)	Conventional (180°F)	High (250°F)
MOR	1.00	0.83	1.00	0.93
MOE	1.00	0.99	1.00	1.03

Values shown are relative to Conventional

Source: [illegible]

MECHANICAL PROPERTIES OF HIGH-TEMPERATURE-DRIED SOFTWOOD LUMBER--RESEARCH NEEDS

by J.F.G. Mackay

1. Identifying the extent of the problem.

To identify species and sizes which are presently high - temperature kiln dried, or can be high - temperature kiln dried, without causing unacceptable visual degrade.

To compare mechanical properties of matched lumber dried at high temperatures and conventional temperatures.

2. Factors causing, or associated with, strength reductions.

According to the available research literature, there are three principal factors involved; (a) the length of time that the wood is exposed to high temperature, (b) the temperature of the wood, (c) the moisture content of the wood. Closely associated with these factors is the permeability, porosity, or "ease of drying" of the wood.

It would be technically possible to isolate each one of these factors in controlled experiments and evaluate the contribution of each to strength reduction. However, although this may desireable, for industry needs we must be able to recognize how these factors interact. Any limitations which are ultimately laid down for the guidance of the drying industry would have to recognize this interaction.

A decision must be made on the sizes of wood specimens to be tested; whether the most useful data would be gained from small clears or full-size members.

3. Applying the findings of 2.

The effects of the causative factors listed above will not be the same for all grades of lumber. It may be that only the higher grades of dimension lumber would be affected by high-temperature drying, since the weakening or down-grading features in other grades (knots, splits, etc.) could have a greater influence on the strength of the member than any reduction due solely to high-temperature drying. Similarly, reduction in strength of a perfectly clear joist with 2 inches of twist should not be assessed in the same way as in a perfectly straight joist with a very large edge knot. There is therefore a need to determine the applicability of strength reductions due to high temperature drying to different grades of dimension lumber.

INFLUENCE OF THERMAL TREATMENTS ON THE MECHANICAL AND CHEMICAL PROPERTIES OF WOOD: A REVIEW OF RESEARCH AT THE MISSISSIPPI FOREST PRODUCTS LABORATORY

By

Warren S. Thompson
and
Robert R. Stevens

Introduction

The response of wood and its constituents to high temperatures has been the subject of many investigations over the years. Much of the research effort in this area has been devoted to empirical determinations of strength losses for various combinations of temperature, heating periods, and heating mediums (2,3,4).[1] This work has shown that heat treatments have differential effects on the various mechanical properties of wood, and that these effects may be temporary or permanent, the former being evident only at the temperature to which the wood is exposed. The permanent effects exist after the wood has returned to normal temperature and, depending upon the severity of treatment, may be manifested by slight to major reductions in strength.

It has long been recognized that the permanent effects of heat on the strength properties of wood result from a partial degradation of the cell-wall material. While the nature of the heat-induced changes in chemical structure has been studied by a number of investigators (5), little information is available on the progressive changes in the mechanical and chemical properties of wood subjected to heat treatments. Likewise, insufficient information exists on the magnitude of the strength losses incurred by wood during kiln drying, steam conditioning, and other commercial heat-processing operations.

This paper summarizes published and unpublished data on this subject from studies conducted by Warren S. Thompson and Robert R. Stevens, either jointly or individually, during the period 1964-1975. A résumé of the experimental procedure, along with representative data, are given for several studies, the results of which have been previously published. Details of procedure and complete data are available in the references cited. A single study not previously reported on is also summarized here.

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[1] Underlined numbers in parentheses refer to literature cited at the end of report.

Study 1: Effect of Thermal Treatments of Short Duration on Toughness and Composition of Wood
(FPJ 14:350-356)

Procedure

Thermal treatments were applied to air-dried toughness specimens of longleaf pine, Douglas-fir, and southern red oak by heating in an oven or steaming in a retort. Nine time-temperature levels were employed with each method. For oven heating temperatures were 150° C, 175° C, and 200° C at times of 20, 40, and 60 minutes. Steam treatments were conducted at gage pressures of 20, 35, and 50 pounds per square inch (126° C, 138° C, and 148° C) at times of 30, 60, and 120 minutes.

Differences in treatment effects on the toughness and chemical composition of the woods were tested by analysis of variance. The relationship between toughness and the changes in chemical composition which attended the treatments was determined by regression analyses.

Results

Toughness was reduced significantly by both oven-heating and steaming treatments (Tables 1 and 2). The magnitude of these reductions was influenced both by the type and severity of treatments imposed and by species of wood.

The effects of oven-heating and steaming were similar in the case of Douglas-fir and red oak. Toughness values for oven-heated and steamed fir averaged across treatment groups were 79 and 76 percent of the control values, respectively. Comparable data for oak were 84 and 81 percent. Thus, for these two species, steaming within the pressure range of 20 to 50 pounds per square inch (125° C to 148° C) had an average effect which was at least as deleterious as oven-heating within the temperature range of 150° C to 200° C. The overall average toughness of oven-heated pine specimens was 81 percent of the control values, while that for steamed specimens was 93 percent.

Table 1. Results of toughness tests on specimens of pine, oak, and fir subjected to thermal treatments of short duration[a]

Treatment (Temp. - minutes)		Percent of control value Pine	Oak	Fir
150° C	20	86	94	94
	40	94	109	87
	60	96	97	92
175° C	20	87	92	85
	40	78	87	74
	60	82	86	71
200° C	20	77	75	70
	40	54	65	70
	60	74	52	67
126° C[b]	30	83	100	88
	60	100	95	85
	120	78	81	81
138° C[b]	30	98	86	77
	60	98	85	77
	120	83	61	71
148° C[b]	30	101	84	76
	60	101	80	64
	120	93	60	64

[a]Each value is the average of five to ten measurements.

[b]Temperatures correspond to steam pressures of 20, 35, and 50 pounds per square inch (gage), respectively.

Table 2.--Analysis of variance: Effect of heating on toughness

Source of Variation	d.f.	F. Oven-heating	F. Steaming
Total	149		
Replications	4	0.66	0.71
Species	2	59.69[a]	10.72[a]
Treatments	(9)	13.31[a]	6.13[a]
Controls x Treated	1	9.44[a]	39.38[a]
Temperature	2	28.84[a]	7.83[a]
Time	2	1.20	15.79[b]
Temperature x Time	4	1.63	.61
Species x Treatment	18	1.74[b]	3.42[a]
Residual	116		

[a]Significant at the 1 percent level of probability.

[b]Significant at the 5 percent level of probability.

Data provided by proximate chemical analyses of the test specimens are presented in Tables 3 and 4 for pine and oak, respectively. These data show that the carbohydrate fraction of both steamed and oven-heated specimens was degraded by the thermal treatments and removed in part with the lignin. The degree to which the specimens were degraded, as judged by the decrease in carbohydrate content and corresponding increase in apparent lignin content, was influenced both by species of wood and the type and severity of the imposed treatment.

Table 3.--Results of proximate chemical analyses of pine specimens (percent of ovendry weight)

Treatment (Temperature -	minutes)	Lignin	Holo-cellulose	Alpha-cellulose	Hemi-cellulose
			CONTROLS[a]		
		30	70	44	25
			OVEN-HEATED		
150° C	20	26[b]	74	45	29
	60	26	74	44	30
175° C	20	29	71	43	28
	60	31	69	41	28
200° C	20	34	66	44	22
	60	34	66	42	24
			STEAMED		
126° C	30	30	70	45	25
	120	32	68	47	25
138° C	30	31	69	45	24
	120	36	64	41	23
148° C	30	32	68	46	23
	120	41	59	39	20

[a]Average of 24 untreated specimens.

[b]Average of duplicate determinations.

Table 4.--Results of proximate analyses of oak specimens (percent of oven dry weight)

Treatment (Temperature - minutes)		Lignin	Holo-cellulose	Alpha-cellulose	Hemi-cellulose
			CONTROLS[a]		
		28	72	39	33
			OVEN-HEATED		
159° C	20	26[b]	74	43	31
	60	25	75	42	33
175° C	20	27	73	40	34
	60	29	71	37	33
200° C	20	33	67	38	29
	60	41	59	41	19
			STEAMED		
126° C	30	25	75	42	33
	120	28	72	39	33
138° C	30	27	73	31	33
	120	34	66	36	29
148° C	30	29	71	39	31
	120	40	60	35	25

[a]Average of 24 untreated specimens.

[b]Average of duplicate determinations.

Steaming altered the chemical composition of the test specimens slightly more than oven-heating. The average decrease in total carbohydrate content of steamed specimens was 10 percent and that for oven-heated specimens was 8 percent. This difference, which was also evident from the results of the toughness measurements, was probably caused by a more rapid hydrolysis in steam than in dry air.

The carbohydrate content of specimens subjected to both heating mediums decreased only gradually with increasing severity of treatment up to the highest level of temperature and exposure period. Most of the reduction in carbohydrate content occurred in the hemicellulose fraction. This fraction was generally more sensitive to the treatments than the alpha-cellulose fraction at all levels of temperature, but the difference between the two was less pronounced in steamed than in oven-heated specimens.

Study 2: Effect of Steaming Treatments on the Toughness and Composition of Wood
(FPJ 19(2):37-43)

Procedure

Specimens for use in this study were obtained from logs from one tree each of loblolly pine and willow oak. One-inch-thick boards cut from the logs were kiln dried, using schedules appropriate for the two species. Specimens cut from the boards were conditioned to a moisture content of 11 percent and dressed to final dimensions of 0.79 by 0.79 by 11 inches.

Specimens of each species were steamed for a period of 0, 4, 8, 12, 16, or 20 hours. Steaming was done in an autoclave at a temperature of 245° F.

Results

The average toughness and chemical composition of steamed and control specimens of southern pine and willow oak are given in Tables 5 and 6, respectively. The toughness of specimens of both species decreased with increasing duration of steaming. Oak was more seriously affected by the steaming treatments than pine. Oak specimens steamed for 20 hours sustained an average reduction in toughness of 49 percent compared to the control specimens. The comparable reduction for southern pine was 27 percent.

Table 5.--Change in toughness and chemical composition of southern pine with increasing duration of steaming at 245° F.

Steaming period (hour)	Toughness[a] (inch-pounds)	Composition (percent of dry weight)[b]			
		Holo-cellulose	Alpha-cellulose	Hemi-cellulose	Lignin
0	316	79	54	25	30
4	285	76	53	23	30
8	266	76	52	23	31
12	263	72	51	21	31
16	249	70	50	19	33
20	233	68	49	19	34

[a]Each value is the average of 60 measurements.

[b]Each value is the average of four analyses.

Table 6.--Changes in toughness and chemical composition of willow oak with increasing duration of steaming at 245° F.

Steaming period (Hour)	Toughness[a] (inch-pounds)	Composition (percent of dry weight)[b]			
		Holo-cellulose	Alpha-cellulose	Hemi-cellulose	Lignin
0	478	85	50	35	21
4	414	80	48	33	22
8	364	77	45	32	22
12	333	74	43	30	23
16	291	72	41	31	24
20	281	71	41	30	24

[a]Each value is the average of 60 measurement.

[b]Each value is the average of four analyses.

All chemical components of both species underwent change as a result of steaming. Each of the three carbohydrate fractions (holocellulose, alphacellulose, and hemicellulose) was reduced by several percentage points, while the apparent content of lignin increased.

The greater part of the reduction in holocellulose content of pine occurred in the hemicellulose fraction. Thus, after 20 hours of steaming, the residual hemicellulose of pine was only 75 percent of that of control specimens, compared to a value of 92 percent for alphacellulose. Both fractions were reduced by the treatments; but, whereas hemicellulose content decreased steadily with increasing duration of steaming, the changes in alphacellulose content were largely confined to exposure periods of 12 hours or longer.

The pattern of variation in hemicellulose and alphacellulose content of oak was quite different from that of pine. Both fractions in oak sustained reductions of about 5 percent during the first 4 hours and thereafter decreased progressively with increasing duration of steaming. After 20 hours, the residual hemicellulose represented 86 percent of the value of the controls, compared to 82 percent for alphacellulose. This result indicates that the alphacellulose fraction of oak is as susceptible to hydrolyses in an atmosphere of steam as the hemicelluloses.

Study 3: Effect of Thermal Treatments on the Mechanical Properties of Southern Pine Poles (FPJ 19(1):21-28)

Experimental Procedure

One hundred and fifty Class 6, 30-foot southern pine poles were selected for use in this study. All poles had a minimum rate of growth of six rings per inch, or 30 percent or more summerwood in the outer 2 inches of radius at the butt end, were straight and free of knots larger than 1 inch in diameter in the lower 10 feet of length, were 24.5 to 27.0 inches in circumference at a point 6 feet from the butt, and had a moisture content of 40 percent or higher in the outer 1/2 inch of radius. All poles were machine peeled.

The poles were assigned to three treatment groups:

Group I - Steam conditioned 14 hours at 245° F.
Group II - Kiln dried for 158 hours. Initial conditions: 140° F, 20° wet-bulb depression; final conditions: 152° F, 35° wet-bulb depression. Final average moisture content: 31.5 percent.
Group III - Kiln dried for 160 hours at dry-bulb temperatures of 170° to 182° F and wet-bulb depressions of 50° to 65° F. Final average moisture content: 13.0 percent.

Immediately following conditioning, all poles were treated with creosote to a nominal retention of 10 pounds per cubic foot, using commercial treating facilities. Group I poles were treated along with a charge of partially seasoned poles, following a steam-conditioning period of 14 hours at 245° F, as previously described. Poles in Groups II and III were treated along with two charges of kiln-dried poles for which identical treating cycles were used. No initial steaming was used, but the two charges were given a 30-minute final steaming before being pulled.

Because of the widely varying moisture content of the poles in the three groups, all poles were stored in water for a period of 6 to 12 weeks prior to testing, thus eliminating moisture content as a variable in the study.

The poles were tested in bending using the cantilever method described by ASTM Standard D 1036-58. After the bending test a 7-foot section was removed from the butt ends of one-half of the poles in each treatment group. From each section two clear specimens 2-1/2 by 2-1/2 by 48 inches were sawn from opposite sides and from points as close to the pole surface as practical. The clear specimens were soaked in water for 2 weeks prior to machining to final dimensions and testing in static bending.

A 36-inch-long piling section, 7.5 ± 0.5 inches on the small end, was cut from each pole furnishing the 7-foot section. The piling sections were stored in water until tested. The piling sections were tested to failure in compression following the procedure outlined in ASTM Standard D 198-27.

Results

The average strength values for poles and piling sections and small clear specimens cut from these poles are given in Table 7.

Kiln-dried poles had significantly higher bending and compression strengths than steam-conditioned poles. The average modulus of rupture at the groundline for steamed poles was only 73 percent of that for poles dried at a maximum temperature of 152° F. Comparable values for modulus of rupture at the point of failure and maximum crushing strength were 72 percent and 82 percent, respectively.

Poles kiln dried at 152° F had higher strength values than those dried at 182° F. The average modulus of rupture at the groundline and maximum crushing strength for the poles dried at the higher temperature were 92 and 94 percent, respectively, of those for poles dried at the lower temperature.

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Table 7.--Results of mechanical tests on Class 6, 30-foot southern pine poles and specimens cut therefrom for three seasoning schedules[a]

Test	Kiln-dried at 152° F	Kiln-dried at 182° F	Steam conditioned
Moisture content (pct)	37	41	36
Specific gravity	0.53	0.52	0.54
Static Bending - 30-foot poles[b]			
Modulus of rupture, groundline ($lb/in.^2$)	7,900	7,280	5,750
Modulus of rupture, breakpoint ($lb/in.^2$)	7,540	7,170	5,450
Modulus of elasticity (10^3 $lb/in.^2$)	1,270	1,160	1,170
Static bending--small clears[b]			
Modulus of rupture ($lb/in.^2$)	8,910	8,000	7,080
Modulus of elasticity (10^3 $lb/in.^2$)	1,480	1,450	1,460
Compression--3-foot piling[c]			
Maximum crushing strength ($lb/in.^2$)	3,290	3,090	2,710
Compression--small clears[c]			
Maximum crushing strength ($lb/in.^2$)	4,260	3,940	3,390
Modulus of elasticity (10^3 $lb/in.^2$)	1,760	1,660	1,670

[a] Underline connecting two or more numbers indicates no significant difference

[b] Average of 50 tests.

[c] Average of 25 tests.

Modulus of elasticity of the test poles was not affected to a significant degree by conditioning method. The pattern of differences in average strength values among small, clear specimens was similiar to that for the poles and piling sections.

Study 4: High-Temperature Drying
of Southern Pine Poles
(FPJ 22(3):17-24)

Freshly peeled pole sections 10 feet long having small-end diameters of 8 to 10 inches were used in the study. Drying was done in a 12- by 12-foot steam-heated kiln down to a target moisture content of 30 to 35 percent using constant dry-bulb and wet-bulb settings of 212° F - 170° F or 225° F - 175° F. Prior to starting a run, a 2-foot section was removed from each of ten randomly selected poles in each charge. Thermocouples were placed approximately 1/4, 1, 2, and 3 inches deep in two poles located on opposite sides of the kiln.

Upon pulling the charges dried at 212° F or 225° F, a second 2-foot section that was adjacent to the first was removed from each of the ten poles. Thus, 20 of these sections were obtained from each of the two charges, ten removed prior to drying and ten afterwards. Four test specimens 1-1/4 inches square were removed from each section, one from each quadrant, as close to the pole surface as practical. The 80 specimens representing each charge were dried at 55° C to a moisture content of about 3 percent, surfaced and crosscut to final dimensions of 1 by 1 by 16 inches, conditioned to a moisture content of 7 percent, and tested in static bending following the procedure of ASTM D 143-52.

Results

Total drying time and final moisture content of poles dried at 212° F were 66 hours and 32 percent, respectively. Comparable data for poles dried at 225° F were 44 hours and 29 percent.

Temperature readings averaged over 4-hour intervals for each of four depths in the sample poles are given in table 8 for poles dried at 225° F. These data show that the temperature at all depths stabilized at about 200° F during the first 24 hours. There was very little variation from this value at depths of 1, 2, and 3 inches during the balance of the kiln run, while the temperature at a depth of 1/4 inch increased gradually, eventually reaching a maximum of 210° F near the end of the schedule. A similar pattern of variation held for poles dried at 212° F, except that temperatures stabilized near 195° F at depths of 1 to 3 inches and 200° F at a depth of 1/4 inch.

Table 8.--Temperature (°F) at various depths in test poles at selected time periods during kiln drying at 225° F.

Drying time (Hr)	Dry-bulb temperature	Wet-bulb temperature	Temperature at depth of 1/4 inch	1 inch	2 inches	3 inches
0	185	132	112	90	82	82
4	217	173	175	160	137	123
8	219	174	184	178	169	164
12	224	176	193	186	185	183
16	223	174	194	187	190	186
20	226	176	200	194	193	193
24	224	176	204	201	201	200
28	225	-	207	202	201	200
32	226	174	205	200	201	200
36	224	177	207	204	204	204
40	226	174	205	203	203	201
44	225	176	210	203	202	202
48	225	174	208	205	203	200

Results of static bending tests of specimens cut from poles dried at 212° F and 225° F are given in Table 9. Average modulus of rupture was 8 and 14 percent lower for drying at 212° F and 225° F, respectively, than for controls; however, average modulus of elasticity was 6 and 13 percent higher, respectively. Only the 14 percent reduction in modulus of rupture for sections dried at the higher temperature was significant.

Table 9.--Results of bending tests on specimens cut from southern pine poles[a]

	Moisture content	Specific gravity	Modulus of rupture		Modulus of elasticity	
	Pct		Lb/in.^{2}	Pct	10^3 lb/in.^{2}	Pct
Control poles	7.8	0.64	18,600	100	2,280	100
212° F poles	7.8	.63	17,100	92	2,410	106
Control poles	5.9	.64	19,300	100	2,180	100
225° F poles	5.1	.64	16,500	86	2,460	113

[a]Each value is the average of 40 tests.

Study 5: Effect of Conditioning Method on Compressive Strength of Southern Pine Piling (Proc. AWPA 65:133-144)

Experimental Procedure

Fifty piles were obtained from each of three geographical locations within the southern pine region for use in the study. All were clean-peeled having a diameter ranging between 6 and 10 inches at a distance of 10 feet from the tip.

A 5-foot section was cut from each of the selected piles. The remainder of the piles were treated. Descriptions of the piling and the treating schedules employed are:

CA series consisting of 50-foot-long partially seasoned piles from North Carolina subjected to air for 1/4 hour at 60 pounds per square inch, steam for 8 hours at 240° F, vacuum for 2 hours at 24 inches, oil for 3-3/4 hours at 175 pounds per square inch, and vacuum for 1/2 hour at 22 inches.

BA series consisting of 35-foot-long air-seasoned piles from Georgia subjected to air for 1/2 hour at 50 pounds per square inch, oil for 3-1/2 hours at 200 pounds per square inch, and vacuum for 3/4 hour at 22 inches.

AD series consisting of 50-foot-long green piles from Louisiana subjected to steam for 15-3/4 hours at 245° F, vacuum for 2-3/4 hours at 150° F, air for 1/4 hour at 40 pounds per square inch, and oil for 2-1/2 hours at 175 pounds per square inch.

Retentions for the three series were 9.8, 12.5, and 10.6 pounds per cubic foot, respectively.

Following treatment, a second 5-foot section was cut from each pile. The two sections from each pile, one treated and the other untreated, constituted a matched pair during the study.

All sections were stored in water for a minimum of 4 weeks to eliminate moisture content as a variable. A 3-foot-long piece was then removed from each piling test section for a compression test. Each of the remainder furnished a 2- by 2- by 8-inch small clear compression test member.

Prior to testing, the ends of the piling sections were banded to prevent brooming. The piles were then tested following the procedure of ASTM Standard D 198-27, except that deformation of the specimens during loading was measured using two dial gages mounted at 180° to each other on the sections.

The 2- by 2- by 8-inch, clear specimens were tested in compression following the procedure of ASTM Standard D 143-52.

Results

The relative average results of the compression tests are presented in Table 10. Strength retention decreased with increasing severity of the duration of steaming as indicated by the data for maximum crushing strength for both piling and small clears. Relative strength retentions for the BA, CA, and AD series which were steamed 0, 8, and 16 hours, respectively, were 98.6, 81.9, and 77.3 percent, respectively.

Table 10.--Average test results--maximum crushing strength and modulus of elasticity of treated specimens relative to those for untreated specimens[a]

	Series BA	Series CA	Series AD	All series combined
	Pct	Pct	Pct	Pct
Piling specimens				
Maximum crushing strength	98.6	81.9	77.3	86.7
Modulus of elasticity	103.5	100.4	91.0	98.7
Small clear specimens				
Maximum crushing strength	102.5	86.2	79.8	90.1
Modulus of elasticity	95.4	95.6	88.7	93.4

[a]Underline connecting two or more numbers indicates no significant difference in treating effect.

The high strength retention for the BA series suggests that the treatment employed with those pilings had no deleterious effect on strength. In contrast, the piling in both the CA and AD series sustained major reductions in strength.

The stiffness of the piling sections was less affected by treatment than was crushing strength. Only the modulus of elasticity of piling sections in the AD series was significantly reduced.

Study 6: Comparison of Mechanical Properties of Southern Pine Dimension Dried at High and Low Temperatures (Unpublished)

Procedure

Variables considered in this study were density, growth rate, and kiln schedule, as follows:

Growth Rate	Density
Fast (>6 rings/inch)	High (>0.47 sp. gr.)
Slow (<6 rings/inch)	Low (<0.47 sp. gr.)

Kiln Schedule

1. Total drying time of 84 hours consisting of 24 hours at 170° F dry-bulb - 150° F wet-bulb, 36 hours at 175°-150° and 24 hours at 180°-150°.

2. Total drying time of 30 hours consisting of 23 hours at 215° F dry-bulb - 190° F wet bulb, and 7 hours at 225°-190°.

3. Total drying time of 25 hours at 225° F dry-bulb - 190° F wet-bulb.

4. Total drying time of 22 hours at 235° F dry-bulb - 190° F wet-bulb.

Sixteen logs--four for each combination of density and growth rate--were cut into 2- by 6-inch lumber. Within each density and growth rate class, one board from each log was randomly assigned to each of the four drying schedules. After drying, four static bending specimens were cut from each piece, yielding 16 specimens per kiln schedule for each of the four combinations of growth rate and density. These specimens were tested following the procedure of ASTM D 143-52 and the resulting data analyzed by analysis of variance.

Results

Test results, averaged across growth-rate and density classes, are shown in Table 11. Treatment effects were significant for both modulus of rupture and modulus of elasticity. Modulus of rupture decreased with increasing dry-bulb temperature. The difference in modulus of rupture between the lowest temperature schedule and the highest temperature schedule was about 12 percent. There was no significant interaction between drying schedule and density or growth rate on modulus of rupture.

Table 11.--Results of static bending tests of small clear specimens cut from southern pine lumber dried using four kiln schedules[a]

Kiln schedule	Modulus of rupture		Modulus of elasticity	
	$Lb/in.^2$	Pct	10^3 $Lb/in.^2$	Pct
1	13,100	100	1,630	100
2	12,300	94	1,470	90
3	12,100	92	1,500	92
4	11,600	88	1,370	84

[a] Each value is the average of 64 tests.

Modulus of elasticity of the specimens did not show a consistent drop with increasing dry-bulb drying temperature; although, the modulus of elasticity for specimens dried using the highest temperature schedule was almost 16 percent less than that for the lowest temperature schedule. Analysis of variance indicated a signficant interaction between drying schedule and density class; however, this is believed to be a spurious result due to several questionable modulus of elasticity values.

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A POTENTIAL PROBLEM IN

HIGH-TEMPERATURE DRYING OF SOFTWOODS

by Robert Erickson

Hypothesis: Honeycomb may be a significant strength-reducing feature of softwood structural lumber that is high-temperature dried.

Analysis:

I. Review of studies dealing with the evaluation of the effect of high-temperature drying on strength. Reports reviewed are those published in the Forest Products Journal and referenced in the 20 literature citations drawn together for the Conference.

In summary --

1 - The majority of the strength tests described in these reports were performed with small, clear wood specimens.

2 - Only two of the eleven reports addressed rather directly the question of a potential honeycomb problem due to high-temperature drying and its possible effect upon strength of the whole piece.

Graham -- Vol. VII, No. 7

This involved the drying of 4" by 8" timbers at several temperatures. Kiln drying at 202°F and xylene drying at 220°F caused extensive honeycomb. This occurred in drying to an average 16 percent moisture content. Honeycomb was so extensive "that considerable cutting was required to obtain small clear specimens from centers of many timbers." Graham concluded that the presence of honeycomb greatly reduced strength and emphasized the need for care in drying such material.

Might the application of temperature higher than those used by Graham but on 2" lumber instead of 4" timbers, also lead to honeycomb?

Salamon, Vol. XXIII, No. 3

The research material was Canadian spruce lumber 2" thick and from 8 to 12 inches wide. The final m.c. of charges averaged 11.5 percent. For the high temperature runs, clear specimens "were cut in such a way as to avoid honeycomb." Salamon concluded that the strength of high temperature dried material "might have been lower had the entire board with included honeycomb been tested." He also concluded that most of the high-temperature drying schedules he employed "produced an excessive amount of honeycomb, therefore precluding their use."

Finally, he found no evidence that modulus of rupture, modulus of elasticity, or maximum crushing strength of the clear specimens cut from the dried dimension lumber were significantly affected by the high-temperature drying.

II. Data from the report by Rufus Page entitled "High-Temperature versus Conventional Methods of Drying Southern Pine Lumber."

1 - Summary of honeycomb observed in the two methods of drying

	None	Mild*	Severe**	Total Number of Pieces Examined
Total H-T	75.8%	22.6%	1.6%	2709
Total Conventional	97.2%	2.8%	--	608

*Mild = "all internal checks were less than 1/32" wide at the widest point"

**Severe = "if the width of one or more bottleneck checks exceeded 1/32 inch"

Conclusion in report: "Honeycomb, then, does not appear to constitute a serious problem in pine lumber dried in high-temperature kilns."

However, Page gives the following M.C. data for this study:

	M.C. 15% max.	M.C. 19% max.	M.C. Above 19%
Total H-T	64% of pieces	82% of pieces	18% of pieces
Total Conventional	68% of pieces	83% of pieces	17% of pieces

Question: What would have been the extent of honeycomb if the lumber had been high-temperature dried to meet the 15% maximum of the SYP rules?

III. Some possible significant interactions of high temperature.

1 - Wet pockets

The favorable strength-reducing condition of wet wood in combination with high temperature would be in effect for longer periods of time in wet pocket areas. Might such areas generally be capable of developing honeycomb following high-temperature drying, as Mackay has shown to be true for wet pockets of aspen?

2 - Areas around knots

Areas of distorted grain and possibly other abnormal features are associated with knots. What is the frequency of honeycomb in these locations under high temperature drying?

3 - Growth ring orientation

Is there serious danger of extensive honeycombs in wide, flatsawn structural lumber? This is suggested by Salamon's study in which the extent of internal degrade was monitored.

4 - Species

Species probably show significant differences in their propensity to honeycomb during drying. Can high-temperature drying thus be routinely applied to softwood structural lumber without better consideration of the natural tendency for the occurrence of a so-called "non-degrading" drying defect such as honeycomb?

In summary, are there some significant strength-reducing interactions of high temperature drying with certain wood types that have gone undetected and should be investigated?

IV. Some personal observations on high-temperature dried aspen--2" material

Drying Schedule	No. of 8' pieces examined	Pieces with honeycomb*
FPL schedule	43	--
210°F-170°F	43	10

*In many cases the internal check occurred in the discolored wood near a knot with no external evidence of honeycomb. In a few severe cases of collapse, the extensive collapse streak was accompanied by a severe internal check. The data was obtained by cutting 5 cross-sections equally spaced along the 8' length.

Theory: Sufficient honeycomb occurs in the routine application of high-temperature drying to softwood structural lumber to constitute a significant strength-reducing factor and one worthy of investigation.

SUMMARY OF WORK ON HIGH-TEMPERATURE DRYING AT NORTH CAROLINA STATE UNIVERSITY

by Robert C. Gilmore

Prior to 1967, some 14 kiln charges were dried as we investigated high temperature drying with southern yellow pine. The main emphasis was placed upon drying with a minimum of degrade and uniformity of moisture content. We did not investigate the effect of high temperature drying on strength properties. The bulk of the early work dealt with 4/4 lumber. Of the 14 charges dried, three were controls (conventional drying up to 180°F), eight were high temperature (230-250°F) and three were high temperature using 8/4 stock. Two levels of air flow were examined--300 and 850 ft./min. The initial average moisture content was 85% but ranged from 24 to 151%.

The influence of air flow is apparent in the following table:

Drying Conditions	Air Flow (f.p.m.)	Average Kiln Time (Hrs.) Drying	Equalizing and Conditioning	Total Time	Average of Final Moisture Content (%)	Range for all Charges (%)
High Temp.	300	11.1	30.5	41.6	9.0	4.8-15.8
High Temp.	850	10.75	14.5	25.25	7.9	4.2-12.8
Conventional	300	63	22	85	9.3	5.9-12.5

The amount of degrade was obtained by examining each board in a charge for checks, splits, twist, bow and crook. The percent of the total number of boards in a charge exhibiting these forms of degrade is listed below. The percentage of volume degrade is also shown.

Drying Degrade

	No. of Charges	Avg. No. of Boards Per Charge	Percent of Boards Showing Degrade: Checks	Splits	Twist	Bow	Crook	Volume Degrade %
H.T. 8/4	3	107	9	4	3	1	3	16
H.T. 4/4	8	145	4	2	4	5	8	4
Conv. 4/4	3	164	6	1	3	8	10	7

Note: Checks reported were primarily surface checks. End checks are usually invisible but subsequent end trimming exposes these hidden end checks. Frequently these end checks penetrate to a depth of 3 to 4 inches--on occasion, to more than twice this amount.

In cooperation with the former Southern Pine Association, NCSU modified a conventional two track kiln for a high temperature drying trial of approximately 56.000 bd. ft. of 8/4 southern pine in widths from 4" to 10" and lengths to 16 ft. In this drying test only one track was used and stack width was 8 feet. The lumber was inspected by an inspector for the Southern Pine Inspection Bureau in this green and dry condition. A portion of the material was also graded after dressing.

In this study 7.4% of the lumber volume dropped by one or more lumber grades due to the drying process. It was interesting to note that 15% of the boards that changed grade after drying actually increased in grade--this was attributed to a reduction in warp during drying. Comments by the lumber inspector and mill personnel indicated that the general appearance of the lumber dried at high temperature was better (less warp) than the conventionally dried material. However, no comparable study was made to determine the degrade involved in their conventional drying.

Drying time (including conditioning) in this high temperature charge was 77 hours (95% to 7%) as compared to 122 hours (to 12%) conventionally. Our major concern was the prevalence of hidden end checking. Based on this one run in a conventional kiln in 1969 (and our earlier laboratory studies), we concluded that drying time could be drastically shortened by high temperature drying but that due consideration must be given to kiln design and construction materials and particularly to lumber stack widths (and its effect on temperature drop) and air flow.

HIGH-TEMPERATURE DRYING OF LODGEPOLE PINE

By

Harry E. Troxell

Lodgepole pine is one of the most widely distributed softwood species of Western United States and Canada. The importance commercially of this species has increased steadily in recent decades and is ranked as the second most important species in Colorado.

Over the last eleven years two studies at Colorado State University have been performed involving the effects of high temperature drying on studs. The initial study reported by Crews and Brown (1,3) emphasized the effect of air velocity on uniformity of final moisture content; drying defects, and strength properties.

A one-step drying schedule was employed in the study with 230° F dry-bulb temperature and 200° F wet-bulb temperature, producing a relative humidity of 55 percent and EMC of 4.9 percent. The drying period was set for all packages at 48 hours. The special stocking design employed permitted the development of three air velocities within each drying package with one fan speed. Periodic weighing of sample studs determined the moisture content changes during the drying period.

Summary of Results of 1965 Study

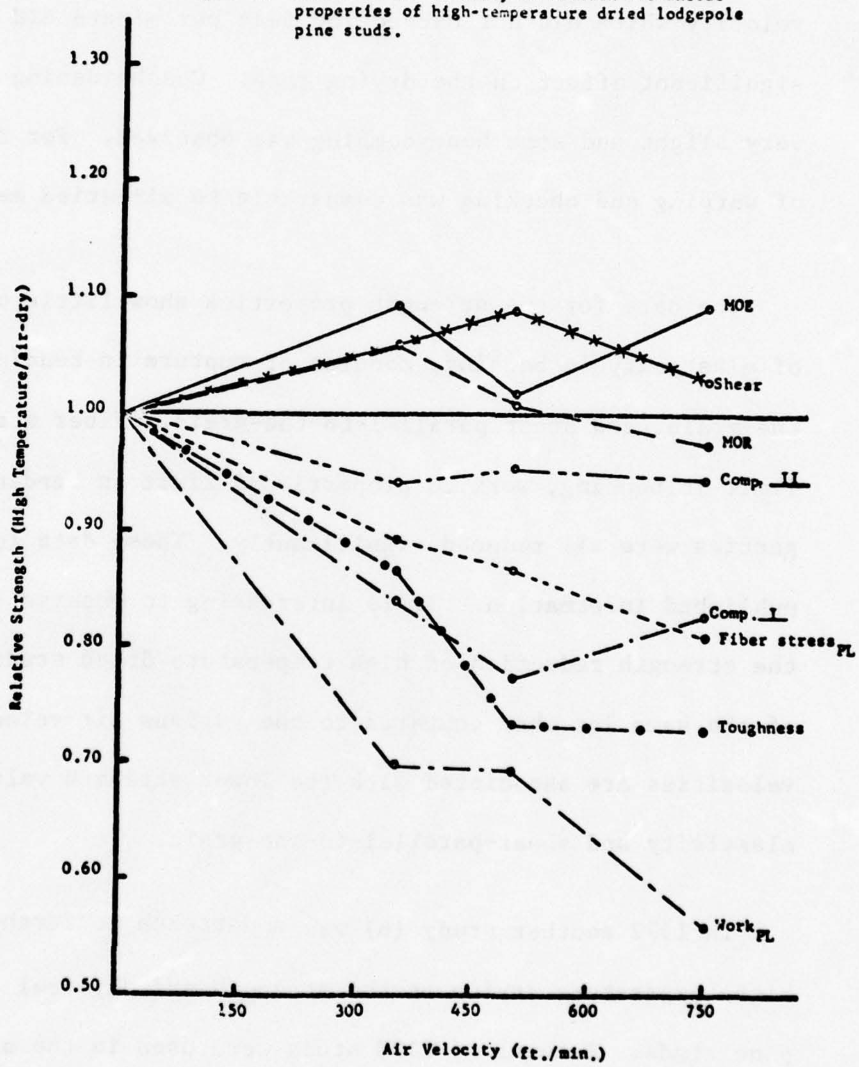
Lodgepole pine studs can be dried at temperatures above the boiling point of water from a green condition to a final moisture content of approximately 11 percent in 48 hours. The effect of air velocity, at least within the scope of

this study, was not significant in its effect on the uniformity of the final moisture content. The drying curves displayed a linear segment where they progressed at a rate of two percent per hour for the first 16-18 hours and then near the thirty percent moisture content the linearity was lost. The air velocity which did not exceed 750 feet per minute did not appear to have a significant effect on the drying rate. Casehardening was noted only to be very slight and some honeycombing was observed. For the most part the amount of warping and checking was comparable to air-dried materials.

The data for the strength properties show little or no reduction in modulus of elasticity in bending, modulus of rupture in bending, compression parallel-to-the-grain, and shear parallel-to-the-grain. Fiber stress at the proportional limit in bending, work to proportional limit in bending and toughness properties were all reduced significantly. These data follow closely other published information. It is interesting to observe Figure 1 which illustrates the strength reduction of high temperature dried studs to the air dried material of the same lot when compared to the various air velocities. The higher air velocities are associated with the lower strength values except for modulus of elasticity and shear-parallel-to-the-grain.

In 1972 another study (6) was undertaken to further examine the effect of high-temperature drying on the strength and physical properties of lodgepole pine studs. A total of 2100 studs were used in the study design. The drying methods (air drying, conventional kiln drying and high-temperature drying) provided the test material for assessing the properties. Again in this study a 48 hour time period was used; the dry-bulb temperature of 220°F and

Figure 1. Effect of air velocity on certain mechanical properties of high-temperature dried lodgepole pine studs.



a wet-bulb temperature of 205° F were maintained. The air velocity in the kiln was maintained at five hundred feet per minute and the studs reached a moisture content of approximately 12 percent in the 48 hours.

Summary of Results of 1972 Study

The major findings (6,8) showing the effect of high-temperature drying on certain strength and physical properties of lodgepole pine studs were determined. The equilibrium of moisture content was significantly lowered as a result of the high-temperature drying. For air dried and conventional kiln dried material EMC averaged for all specimens to 12.1 percent but for the high temperature dried studs the EMC was 10.8 percent. A comparison of shear strength parallel-to-the-grain showed no significant difference between the kiln-dried and high-temperature dried materials.

The static bending results are summarized in Tables 1 and 2. Examination of these data is helpful to establish the differences that exist among the three drying methods.

Table 1. Statistical summary for static bending showing modulus of rupture, modulus of elasticity, and stress at proportional limit for the three drying methods.

Drying Method	Property: Mean	Variance	Standard Dev.
		MOR ($x10^3$ psi)	
Air-dry	10.411	.843	.918
Kiln-dry	9.842	1.856	1.362
High-temperature-dry 1/	10.057	1.622	1.273
High-temperature-dry 2/	9.338	3.155	1.776
Published data (9)	9.400		
		MOE ($x10^6$ psi)	
Air-dry	1.176	.0 175	.132
Kiln-dry	1.119	.0256	.160
High-temperature-dry 1/	1.164	.0303	.174
High-temperature-dry 2/	1.142	.0259	.161
Published data (9)	1.340		
		σ PL ($x10^3$ psi)	
Air-dry	6.040	.473	.688
Kiln-dry	5.602	1.095	1.046
High-temperature-dry 1/	5.882	.558	.747
High-temperature-dry 2/	5.461	.467	.683
Published data (9)	6.700		

1/ Adjusted to 10.8 percent moisture content

2/ Adjusted to 12.0 percent moisture content

Table 2. Summary of "t" values showing modulus of rupture, modulus of elasticity, and stress at proportional limit for the three drying methods.[1/]

Source of Variation	MOR	MOE	σPL
Kiln-dry vs. High-tempetature-dry	1.03 N.S. (1.99)*	1.68 N.S. (0.877)N.S.	1.93 N.S. (1.13)N.S.
Kiln-dry vs. Air-dry	3.09**	2.85**	3.09**
High-temperature-dry vs. Air-dry	2.02* (4.77)**	.894 N.S. (1.86) N.S.	1.35 N.S. (4.66)**

1/ "t" values for high-temperature drying adjusted to 12.0 percent moisture content are shown in parentheses. All other high-temperature drying data have been adjusted to 10.8 percent moisture content.

N.S. = Not significant at .05 level
* = Significant at .05 level
** = Significant at .01 level

In considering the modulus of rupture, no difference occurs between the kiln-dried and high-temperature-dried studs. The differences between the high-temperature-dried and air-dried are just barely significant at the .05 level. Comparison of the kiln-drying and the air-drying, however, shows that the modulus of rupture differences are highly significant. In discussion, it is reasonable to assume that drying does affect the ultimate strength of wood. The extent to which the drying conditions alter the strength is quite variable. In this study, therefore, it has been shown that the modulus of rupture of the high temperature drying compares favorably to either conventional kiln drying or air-drying for lodgepole pine. The greatest differences are found between kiln-drying and air-drying.

In analysis of the modulus of elasticity and stress at proportional limit, the information collected for the test studs showed similar relationships as for the modulus of rupture. Discussion of these results needs to emphasize that

differences in the equilibrium moisture content for 12 percent conditions are caused by a change in hygroscopicity of the high-temperature dried wood. This anomaly is very much in evidence and was not observed in either air-drying or kiln-drying.

The color phenomenon observed was extremely interesting. Distinct color characteristics were noted in all the test wood regardless of position from the log or in the stud. Cech and Huffman (2) reported this as a surface appearance, but this study showed consistent color characteristics throughout all the test material. The air-dried specimens had the commonly recognized white appearance. The kiln-dried material showed a light yellow color and the high-temperature wood was a distinctive and recognizable darker yellow color. The primary reason for these color differences in over two thousand pieces is attributed to pyro-chemical change of the extractives. The higher the temperature the deeper the yellow tones of the wood become.

The observed warpage of the air-dried studs was found to be minimal and confined to the upper two courses of the packages. Previously collected information (1) at Colorado State University found the high-temperature dried studs had seven percent more degrade than air-dried material. In this study, warpage in the kiln-dried lumber was greater than in either the air-dried or the high-temperature dried material. This latter fact corroborates published data (2, 4, 5, 8).

These results assuredly indicate that high-temperature drying has a place in the drying field. Refinements in equipment, and the behavior of various species when subjected to high-temperatures remain topics for much more research in order to better understand the drying parameters and their effects on wood quality and strength properties.

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EFFECT OF HIGH TEMPERATURES ON THE RATE OF DEGRADATION AND REDUCTION IN HYGROSCOPICITY OF WOOD

by C. Skaar

Summary: Exposure of wood to high temperatures has at least two effects on its properties. These are, reduction in strength of the wood at a given moisture content, and reduction in hygroscopicity. These two factors are interrelated insofar as the subsequent strength of the wood in service is concerned because they have opposite effects on the strength at given exposure conditions. Thermal degradation occurs much more rapidly in wet than in dry wood at a given temperature. Reduction of hygroscopicity is clearly evident when dry wood is heated but the effect of heating wet wood is not as well defined. The effect of high temperatures on aggravating defects is not clear.

When wood is dried there is a complex interaction of moisture content, temperature, and time at any given location in the wood. This interaction varies with location in the wood, that is, it is different at the surface than near the center of a given board. Furthermore, because of different required drying times, it is different for thick than for thin lumber and for poles compared with lumber. It also varies among different species because of differences in initial moisture contents and rates of moisture movement among these species. A particularly high degradation may occur in boards which are passed through a drying cycle twice because of wet spots.

The effect of high-temperature drying (HTD) of lumber (drying at temperatures above 212°F or 100°C) on its subsequent mechanical properties is a subject of potentially critical importance to the wood construction industry. At the U.S.F.P.L. conference of February 25 and 26, 1976, it was evident that there were areas of disagreement among some of the participants as to the extent of mechanical degradation which results from drying structural lumber at the high temperatures presently used or contemplated for use in industry. Certain studies have indicated that reduction in strength was negligible while others have indicated appreciable reduction in such important properties as the modulus of rupture (MOR) in bending. Furthermore, there have been few attempts to relate the mechanical testing data to basic studies of the kinetics of thermal degradation and of other thermal effects such as reduction in hygroscopicity, increased rates and modified mechanisms of moisture movement and of rheological flow, phase changes and modification of chemical constituents, reorganization of cell wall configuration at both microscopic and submicroscopic levels, etc.

Some of these factors have been discussed in a recent paper by Hillis (1975) of Australia, where HTD is also developing rapidly as an industrial practice. Stamm (1964) also discusses additional factors, as have others.

It is the purpose of this paper to attempt to sort out (synthesize) some of these factors in the light of the recent Madison conference in the hope of clarifying our understanding of the many factors involved in the effect of HTD on the mechanical properties of wood. In order to do this the subject areas will first be discussed separately after which their interrelationships will be treated. It should be pointed out that this discussion is not original and is essentially a recapitulation of the work of others who have been active in this field.

The subject areas will be treated in the following order:

1. Kinetics of thermal degradation
2. Thermally induced hygroscopicity changes
3. Drying rates at high temperatures
4. Rheological effects of high temperature drying
5. Synthesis of these factors

1. Kinetics of thermal degradation.

The thermal degradation of wood exposed to high temperatures generally appears to proceed as a first-order chemical reaction (Stamm, 1964). In such a reaction, the rate of degradation dx/dt is proportional to the amount (a-x) of unreacted material still remaining, where a is the original amount of material, and x is the amount which has reacted. In equation form this can be written as

$$dx/dt = K\ (a-x) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1),$$

where K is the rate constant. Equation (1) can be integrated to give

$$K = -\ln\left[(a-x)/a\right]/t \ \ldots\ldots\ldots\ldots\ldots\ldots (2).$$

According to equation (2) the logarithm of ((a-x)/a), the fraction of unreacted material remaining, is linearly proportional to the length of time t that the reaction has proceeded. More complex equations are required when reactions of higher than first order are involved. Nevertheless, equation 2 appears to satisfy the rate of thermal degradation of dry wood despite the fact that several reactions are occurring simultaneously when wood is heated. For wood heated in the wet condition, however, this simple relationship does not appear to hold and the curves of log ((a-x)/a) are non-linear.

The rates of thermal degradation of wood have been expressed in terms of a number of wood properties. These included weight loss, loss in various strength properties such as toughness, modulus of rupture (MOR), modulus of elasticity (MOE),

tensile strength, etc. Similar rate equations have also been applied, with some modification, to changes in hygroscopicity and associated dimensional stabilization which accompany the heating of wood in a dry atmosphere.

Increasing the temperature of wood drastically increases the rate of thermal degradation. This increase appears to be of the the type predicted by the Arrhenius rate equation which can be written

$$K = k(\exp(-\Delta H/RT)) \qquad (3)$$

where K is the reaction rate at the absolute temperature T (Kelvin degrees), ($-\Delta H$) the activation energy for the reaction, expressed in calories per mole if the gas constant, R, is given as 1.987 calories per mole-degree, and k is an empirical constant. If the rate constant K_1 is known at some temperature T_1 its value K_2 can be calculated at some other temperature T_2 by integrating equation (3) into the form,

$$\ln(K_2/K_1) = (-\Delta H/R)((1/T_2)-(1/T_1)) \qquad (4).$$

It is thus possible to calculate the ratio of thermal degradation of wood at any temperature, T_2, if it is known at some given temperature, T_1, provided the Arrhenius equation applies and that the activation energy ($-\Delta H$) is known. Since the rate constant K and total reaction time t are inversely related according to equation (2), equation (4) can also be written as

$$\ln(t_1/t_2) = (-\Delta H/R)((1/T_2)-(1/T_1)) \qquad (5),$$

where t_1 and t_2 are the reaction or heating times at which the same degree of degradation occurs at the corresponding temperatures T_1 and T_2. From this equation the time required for a given degree of thermal degradation at one temperature, say T_2, can be estimated if the time t_1 for the same degradation is known for temperature T_1, and if the activation energy ($-\Delta H$) is known.

The applicability of the Arrhenius equation to the rate of thermal degradation of wood is illustrated by Figure 1, taken from Millett and Gerhards (1972).

Each line in the figure shows the linear relationship between the logarithms of the time t required for wood samples heated in an oven at a given constant temperature to be degraded to a given percentage of the original wood strength in terms of the modulus of rupture (MOR). For example, the lowest curve in Figure 1 shows such a relationship for a residual MOR of 95 percent. From the slope of this curve, the activation energy ($-\Delta H$) for the degradation reaction can be calculated by using equation (5) in the form

$$-\Delta H = +R(d\ln t_{95}/d(1/T)) \quad (6).$$

The equation of this curve as given by Millett and Gerhards (1972) is

$$\log t_{95} = -13.940 + 5925/T \quad (7),$$

from which the activation energy can be calculated, using equation (6), as follows,

$$-\Delta H = (1.987)(2.303)(5925) = 27{,}108 \text{ cal/mole} \quad (8),$$

where $2.303 \log t_{95} = \ln t_{95}$.

Figure 2 compares the curves obtained by Millett and Gerhards (1972) of $\log t_{95}$ against $1/T$ using three different criteria for evaluating thermal degradation, based on the mean results for six wood species, all oven-heated in dry air. The three criteria are, MOR, MOE and dry weight, all for a residual of 95 percent of the original value, or 5 percent reduction in value. It is clear from the figure that they all satisfy the Arrhenius relation and have approximately the same slope, indicating that the activation energy ($-\Delta H$) is the same for all three criteria. However, the MOR curve is displaced downwards by approximately one decade from the other two. This indicates that the time required to attain a 95 percent residual MOR is only about 0.1 as long as that required for a 95 percent residual MOE, or of dry weight, for a given heating temperature under these dry heating conditions. This agrees with findings of Stamm (1956), who also points out that heating dry wood in the presence of oxygen, as is the case in the oven-heating data cited above, results

in more rapid degradation than heating in an oxygen-free atmosphere.

Heating wood under wet conditions at a given temperature degrades it in a much shorter time than under the dry conditions discussed above. McLean (1951, 1953, 1954, 1955) has studied the comparatives rates of thermal degradation of wood heated un der dry and wet conditions. Stamm (1956) has used these data, plus additional data based on his own studies, to compare the rates of thermal degradation of wood heated under these different conditions. These data can be expressed in different ways in order to compare the effects of different heating media. For example, according to Stamm (1956), the reaction rates for heating wet wood in water is 10 or more times greater than for heating dry wood in an oven at comparable temperatures. Furthermore, the activation energy ($-\Delta H$) for heating wet wood is about half that for heating dry wood, indicating that a different mechanism is involved.

In terms of the time $t_{.95}$, required to degrade wood to 0.95 residual MOR, it requires approximately 1250 hours (53 days) of oven-heating of dry wood at 100°C (212°F) but only about 16 hours (0.67 day) of steaming of wet wood at the same temperature to achieve the same degradation in MOR. At 120°C (248°F) the corresponding times are 200 hours (8 days) and 5 hours (0.2 day) for the dry and wet heating modes. Calculations of degradation times for 0.95 residual MOR can be calculated for other heating temperatures by use of equation (5) if the activation energies are known. These have been determined and are approximately 27,000 calories per mole for degradation of dry wood and about 16,000 calories per mole for wet wood.

The rate of thermal degradation of dry wood appears to follow the form of a first order reaction. Therefore, it is possible to use equation (2) to calculate the times required to degrade dry wood to other residual MOR's than .95 at a given temperature by rearranging equation (2) into the form,

$$t_2/t_1 = \ln(MOR_2)/\ln(MOR_1) \qquad (9)$$

where t_1 and t_2 are the heating times required to reduce the residual MOR's to $(MOR)_1$ and $(MOR)_2$, respectively. Thus, if $t_{.95}$ is the time required to degrade the wood to a residual MOR of 0.95, the time $t_{.90}$ required to degrade it to 0.90 residual MOR is given by

$$t_{.90} = (t_{.95}) \ln(0.90)/\ln(0.95) = 2.054\ t_{.95} \qquad (10),$$

or somewhat more than twice as long. For degradation in strength properties of 10 percent or less the approximation can be made that the degree of degradation is a linear function of time or that

$$t_2/t_1 \approx (MOR_o - MOR_2)/(MOR_o - MOR_1) \qquad (11)$$

where MOR_o is that for the original unheated wood. The degradation of wet wood with heating time at a given temperature does not appear to follow a first order reaction nor does the Arrhenius equation appear to apply as well as for the degradation of dry wood. Nevertheless, Stamm (1956), has shown that apparent activation energies calculated from the data of McLean (1954) over limited temperature ranges are only about half the magnitudes of those for oven-heating. Furthermore, the rate of thermal degradation is in the order of ten times higher for wet than for dry wood. Table 1 shows a comparison of the times required to attain various degrees of degradation in the modulus of rupture for wood heated in the oven and also in water and steam. Also shown are results calculated from heating the wood in a live steam atmosphere in which case the rate of degradation is even more rapid than for heating in water.

2. Thermally induced hygroscopicity changes

Exposure of wood to high temperatures reduces its subsequent hygroscopicity when it is returned to normal temperatures. This effect occurs simultaneously with thermal degradation, and is an important factor in evaluating the effect of HTD on the mechanical properties of wood because of the inter-dependence of moisture content and strength.

Before discussing the effect of temperature on hygroscopicity, we will discuss briefly the means of evaluating reduction in hygroscopicity. This may be done either as an increase in dimensional stability or as a reduction of moisture changes associated with a given change in exposure conditions. It is convenient to define the moisture expansion coefficient X_m, as

$$X_m = 100(\Delta L/L)/\Delta M \qquad (12)$$

where $\Delta L/L$ is the fractional change in dimension (radial, tangential, volume, etc.) associated with a change ΔM in moisture content. The coefficient X_m is generally not affected by thermal treatments unless they are very severe (Stamm, et al, 1955, Kozlick, 1973), that is the dimensional change per unit moisture change is generally the same for wood dried at low or high temperatures unless appreciable drying stresses are present.

The anti-shrink efficiency AE, is customarily defined as

$$AE = 100((\Delta L_o/L_o) - (\Delta L_t/L_t))/(\Delta L_o/L_o) \qquad (13)$$

where $\Delta L_o/L_o$ and $\Delta L_t/L_t$ are the fractional changes in dimensions of the untreated and treated wood when both are exposed to the same humidity change ΔH. If the moisture expansion coefficient X_m is the same for untreated or treated wood, the anti-shrink efficiency can also be defined as

$$AE = 100\ (\Delta M_o - \Delta M_t)/\Delta M_o \qquad (14)$$

for the same humidity change ΔH.

Equation (14) can be written in terms of the EMC of treated and untreated wood at a given relative humidity H by assuming that the humidity range ΔH is from zero to some convenient or standard humidity H. In this case, equation (14) can be written

$$AE = 100\ (M_o - M_t)/M_o \qquad (15)$$

where M_o and M_t are the EMC's of the untreated and treated material at the same humidity. It may be necessary to distinguish between AE based on dimensional changes from that based on hygroscopicity changes, if X_m is different for treated and untreated wood. In this case, the latter can be designated with the subscript m.

The rate of reduction in hygroscopicity of wood by heating in the dry condition appears to follow the Arrhenius relation in regard to the time-temperature combination required for a given reduction in hygroscopicity. The effect of heating wood in the wet condition results in less well-known changes in hygroscopicity compared with heating in the dry condition. In contrast to the case of thermal degradation, there is only a minor effect on reduction of hygroscopicity whether dry wood is heated in the presence or absence of air or oxygen.

Using data of Stamm et al (1955), the times in hours required to achieve three different degrees of anti-shrink efficiencies are given in Table 2 for heating temperatures of 200°, 250°, and 300°F. According to the table, the HTD schedules currently in vogue, or contemplated, will result in a 5 percent or lower level of anti-shrink efficiency based on moisture sorption. This appears to be lower than has been observed in dry-kiln practice, where wood which has been kiln-dried at higher temperatures has maintained an appreciably lower moisture content than that dried at lower temperatures. For example, using data of Salamon et al (1975) the mean

moisture contents in June for wood samples air-dried, conventionally kiln-dried and dried at 220°F and 245°F temperatures were 17.1, 14.7, 13.8, and 13.2 percent, respectively. Neglecting for the moment the differences between air-dried and kiln-dried material which is attributable primarily to hysteresis since the air dried stock was never subject to very dry atmosphere during drying, we can calculate the anti-shrinkage efficiencies of the two sets of HTD material based on the conventionally kiln-dried stock. Using equation (15), the AE for the 220°F stock is

$$AE_{220} = 100(14.7 - 13.8)/14.7 = 6.1\%,$$

and that for the 245°F material is

$$AE_{245} = 100(14.7 - 13.2)/14.7 = 10.2\%.$$

It is clear from these figures that the apparent anti-shrinkage efficiencies are higher than might be expected based on the data given in Table 2. This may be because of lower EMC conditions in the kiln at the higher temperatures and the consequent increased hysteresis effect which can cause an anti-shrink efficiency based on equation (15) of the order of 20 percent.

Regardless of the cause of reduced EMC for wood dried at high temperatures, the point is that a lower EMC will have an effect on the mechanical properties of the wood in use, or at time of test. There are two methods for evaluating the effect of HTD on the mechanical properties of wood, based on the observed change in hygroscopicity. One of these is to compare the properties of the wood at equilibrium with a given humidity condition, in which case the wood dried conventionally will have a lower EMC. This we will designate as the constant humidity condition (CHC). The second method, designated as the constant moisture content condition (CMC) compares the properties of the wood at the same moisture content. Since most testing is done on samples equilibrated to the same humidity condition, it is necessary in this case to

adjust the calculated values to the same moisture content for all samples. This is done on the basis of correction procedures established on the basis of known moisture content-strength relationships for wood. For example, the modulus of rupture increases approximately four percent per one percent decrease in wood moisture content.

Reported studies of the effect of high temperatures on the mechanical properties of wood have used the CMC values in some cases and the CHC values in others. In evaluating the effect of HTD on the mechanical properties of wood it is important to distinguish between the two methods of evaluation. From the viewpoint of the fundamental mechanism of thermal degradation of wood it is probably best to use the CMC method, but for practical evaluation of the effect of HTD on the strength of wood in service the CHC method is probably more realistic. However, in the latter case, it is also important to know the degree of permanence of the reduced hygroscopicity resulting from HTD, although according to Stamm, et al (1955) the stabilization caused by heating is permanent.

In the previous paragraphs we have been discussing essentially the strength of clear defect-free wood. Most lumber, however contains defects of various kinds and it is not known whether or not HTD accentuates the strength-reducing attributes of these defects. It is conceivable, for example, that the tissues around knots may be degraded more severely by HTD than clear wood insofar as the mechanical properties are concerned. On the other hand, it is also conceivable that the high temperatures used may minimize the effects of discontinuities around knots by virtue of the softening effect and consequent reduction of stresses.

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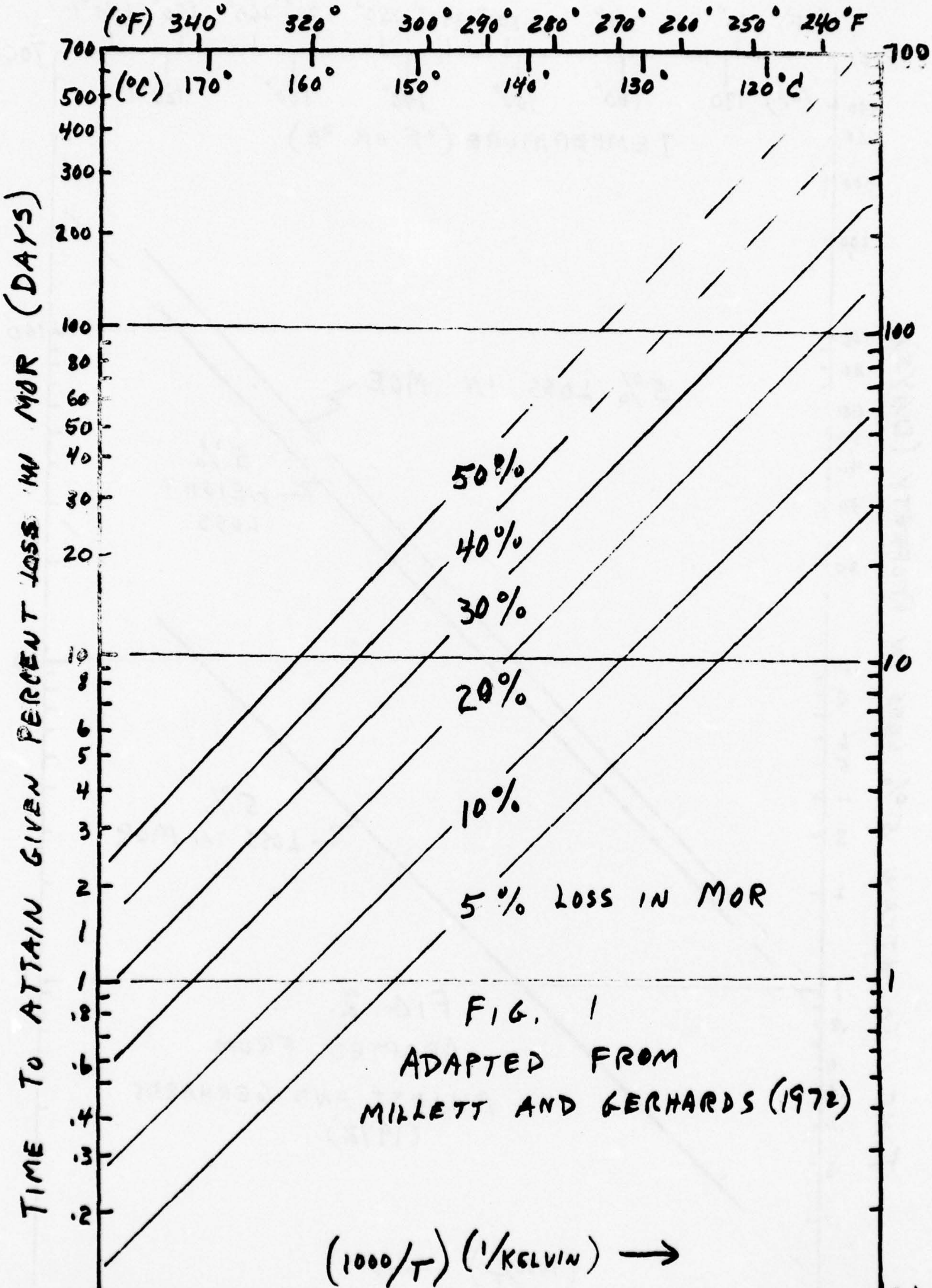

FIG. 1
ADAPTED FROM
MILLETT AND GERHARDS (1972)

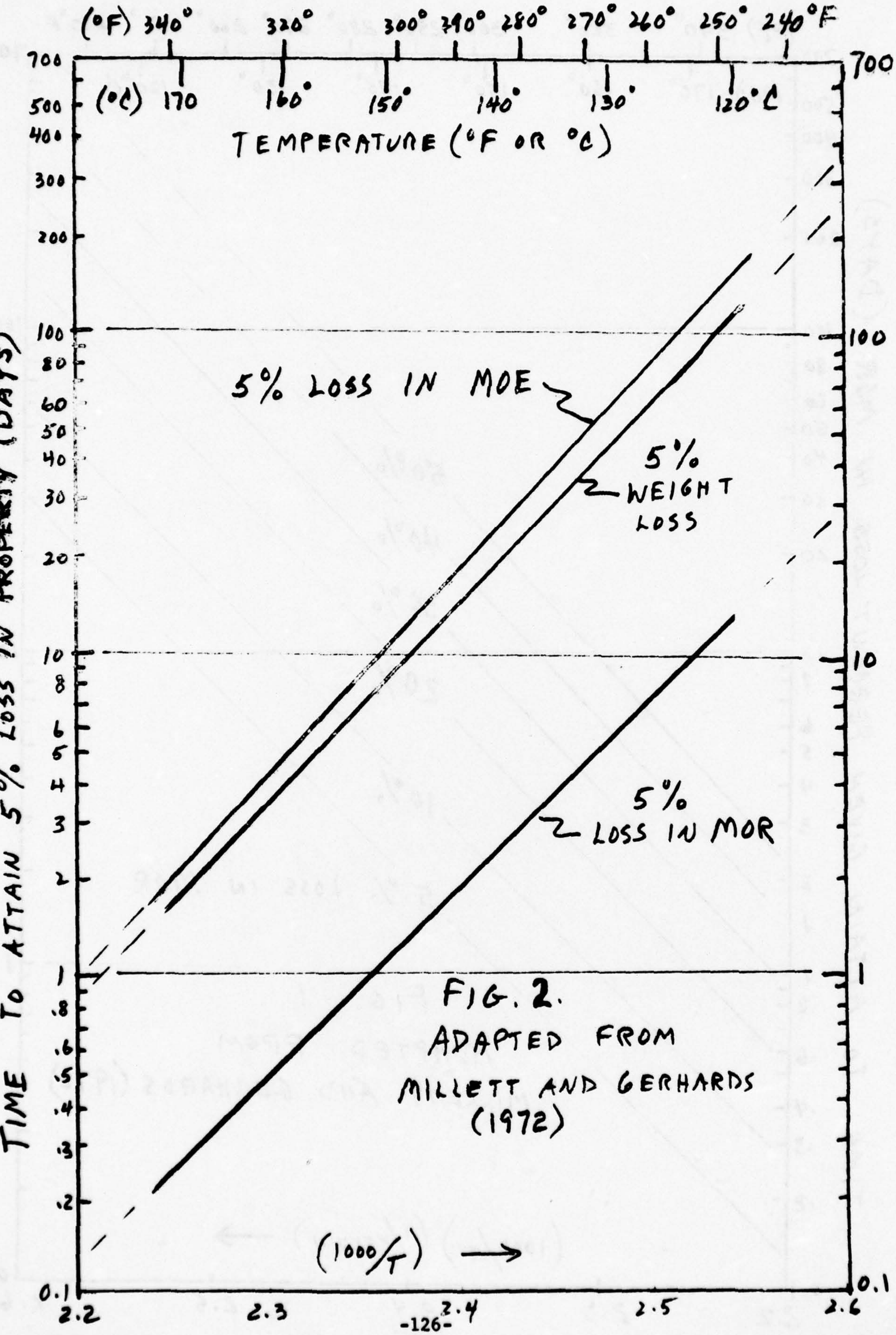

FIG. 2.
ADAPTED FROM
MILLETT AND GERHARDS
(1972)

Table 1. Heating time required (hours) for the residual Modulus of Rupture (MOR) to decrease to 0.95, 0.90, and 0.80 of its original value for Douglas fir and Sitka spruce heated in an oven in water and in steam at temperatures of 200°F, 250°F, and 300°F (from data of McLean, 1953, 1954, 1955)

Heating Condition	Hours to $MOR_{.95}$			Hours to $MOR_{.90}$			Hours to $MOR_{.80}$		
	200°F	250°F	300°F	200°F	250°F	300°F	200°F	250°F	300°F
OVEN (DRY)*	2000	160	16	3200	400	40	5600	708	71
WATER (WET)	80	5	0.4	240	9	0.8	1800	38	2.4
STEAM (WET)	20	3.5	0.2	50	6	0.4	100	24	1.2

*Rates of degradation when dry wood is heated in the absence of air are somewhat slower than for oven-heating

Table 2. Hours of heating time required to produce anti-shrink efficiencies (AE of 5, 10, and 20 percent for Sitka spruce heated under dry conditions at temperatures of 200°F, 250°F, and 300°F (from data of Stamm et al, 1955)

Hours to 5% AE			Hours to 10% AE			Hours to 20% AE		
200°F	250°F	300°F	200°F	250°F	300°F	200°F	250°	300°F
1000*	80*	4*	4,000*	210	15	15,000*	1000	50

*Estimated

CTB
CENTRE TECHNIQUE DU BOIS

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February 24, 1976

Mr. Billy Bohannan, Assist. Director
Wood Engineering Research
U.S. Forest Service
Forest Products Laboratory
P.O. Box 5130
Madison, Wisc. 52705 U.S.A.

Dear Mr. Bohannan:

I received on February 19 your letter to Dr. Fred Dickinson regarding the Feb. 25 & 26 high temperature drying conference at Madison and his letter back to you. I am very sorry to have to miss this meeting and even more so that this letter will not reach you until the meeting is over. I would like, however, to not only express my personal interest in the problem but offer my services for what they may be worth.

Realizing that most of these aspects were probably covered in the conference and lacking a complete understanding of the exact final objectives of the program I would, nevertheless like to make several general comments for your consideration:

1. Greater emphasis should I think be placed on the statistical analysis of the mechanical properties being tested, particularly in regard to variability. Perhaps the steering committee can establish some guidelines as to the most appropriate and efficient experimental design of such tests, including the final statistical analysis.

2. I would also hope that greater use of full-sized specimens rather than small clear specimens will be encouraged; I feel any real reduction in strength may result more from problems with knot loosening or fall-out or checking than from thermal degradation.

3. Although not now common practice with American industry, I think we would be amiss not to include in an evaluation of this nature the following:
   a. Higher temperatures, that is up to 350°F. I say this in light of the apparent recent success in Australia in drying dimension lumber at temperatures near 300°F.
   b. The use of presteaming treatments for warp reduction should also be considered as this has real potential to our industry and may become common practice with certain species.

c. The question of whether higher drying temperatures will significantly affect gluing properties of solid wood, and subsequently strength of laminated products, should also be resolved. While one might argue that there are sufficient data on this question from veneer drying studies, the vastly different temperature-moisture content-time relationships in the drying of these two materials raises some doubts in my mind.

d. Hopefully the study will not be limited to softwoods, but that some hardwood species will be included--at least to the point that generalizations might be possible as to effects on any hardwoods used in the future.

4. It is essential to develop some sort of numerical expression of the severity of drying a given charge has been exposed to. This will not only be necessary in comparing research results from different workers but ultimately in predicting strength losses (if significant losses are indeed found) to untested conditions etc. Since any losses in strength due to thermal degradation will depend upon the wood temperature-moisture content-time history of the piece, all of these factors must be taken into account; although for simplicity, drying temperature will undoubtedly be used for wood temperature. It seems to me that George Bramhall's recent work on "drying effort" calculations might have some potential here with modification.

5. The question of drying using more conventional convective heat transfer methods as compared to conductive methods (Peter Koch's recent work with southern pine for example) should also be considered. I say this in light of the fact that for the same drier temperature, conductive methods or processes with their inherently higher heat transfer rates may lead to higher wood temperatures, at least at the surface.

6. In the preparation of the position paper and during the preliminary problem analysis phase, I hope the Russian research carried out in the 1960's on this subject can be more fully examined. The translation services of the Forest Service would be necessary as very few of these articles have ever been translated, I believe. I have included a list of these from my files.

7. Lastly I would certainly hope that the efforts of the steering committee and any ultimate further research will be transmitted outside the United States in an effort to gain even greater input. The IUFRO Working Party on Drying might provide a good opportunity of accomplishing this.

Please forgive the length of these comments, but I did want to pose them. I should add that I by no means mean to imply that all of the above should be researched. There is, I think, probably sufficient data already available to answer some, and all that is needed is a careful evaluation. Please let me know if there is anyway in which I might contribute.

Yours truly,

Donald G. Arganbright, Project Leader, University of California, Forest Products Laboratory

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Some Thoughts on High Temperature Drying and Wood Strength Relationships -- the Need for Additional Research

by
Dean W. Huber

Let your fingers do the walking through the yellow pages -- and you'll probably find an answer to your question. But let your fingers walk through the literature to review the effect of high temperature drying on wood strength -- and you'll become confused. Being blunt about it: research results are not consistent.

Is there a species effect? Numerous tests on Douglas fir indicate a reduction in strength when dried at temperatures above 200° F. But the southern pines have shown no statistical reduction in strength. Between these two extremes are the white firs, spruces, and hemlocks which have very erratic test results.

Why is this a serious question that needs to be resolved? There are two answers: the implied effect on building codes and structural design, and the implied effect on mill processing and competitive marketing. If high-temperature drying is species selective in its effect on strength, then each sawmill manager will need to decide the trade off between the production advantage of high-temperature drying and sales advantages of higher strength wood. This will lead to tremendous confusion in the industry. It's a confusion that will filter down to the

architect, design engineer, and building contractor.

The solution is not to ignore the questions, but to continue research until constant results are established. This research should include a search for why the effects (if any) occur, as well as what species are affected. Although most researchers have followed ASTM standards for strength test, very few researchers use the same procedure for drying. Therefore a major requirement in any forthcoming research is to establish a standard test procedure for the drying method.

This standardized drying procedure should include the following as commonly found in industry:

sticker thickness	duration of presteaming
leaving air velocity	degree of equalizing
width of load	duration of conditioning
dry bulb schedule	use of matched test samples
wet bulb depression	final moisture content
full size members	final moisture gradient

This indicates the need for a well-designed research study with diligent recording of data and the use of sophisticated methods. Another vital requirement is the use of replicate testing. One or two studies are not adequate to evaluate an industry-wide (and continent-wide) problem. Nor can a limited number of studies

properly evaluate the broad range of specific gravity and permeability per species group.

After the laboratory research is completed, the results should be confirmed in commercial drying systems. Of specific concern is the effect of wood location in the kiln charge and the temperature range over which any effects occur. For example, will there be a difference in response from wood located on the periphery of the kiln charge versus the geometric center of the load? if so, is the difference due to drying temperatures, drying rates, or duration of exposure to high temperatures? There are several ways to control drying rate and exposure time while maintaining the same drying temperature and the increased production of high temperature drying.

Included in the laboratory testing should be a chemical evaluation of wood substances and the kiln atmosphere. Some people attribute the indicated strength reduction of Douglas-fir to its acetal content and low pH. Other people compare the permeability of various species, i.e. Douglas-fir versus southern pines. The ultimate answer to the riddle may be at the chemical level of the wood substance rather than the macro level of drying temperatures tested by non-standard drying procedures.

This entire subject is a realistic industrial dilemma. Is the apparent effect one of temperature alone or complex relationship with other factors such as drying rate, final moisture content and gradient, exposure time, diffusion coefficient, etc.

In practice, lumber companies dry at high temperatures because of reduced drying time, reduced drying cost, and increased dry kiln production. Therefore, if drying temperature has a significant effect on strength these companies may have some severe consequences. However, if the effect is a combination of several factors, then we may be able to alter one or more of the other factors and minimize the overall effect.

I would like to see continued and coordinated research to isolate the variables that cause variation. The current data and literature has too many conflicting results to substantiate any firm conclusions.

III. REFLECTIONS ON RESEARCH NEEDS:

FROM AN ENGINEERING VIEWPOINT

By

C. C. Gerhards and W. L. Galligan

Past research has dealt with a variety of kiln schedules and specimen types. As a result, it is difficult to generalize about the effects of high temperature drying on mechanical properties of wood. Future research in the area of high temperature drying should be coordinated where possible so that the effect on any given wood property can be generalized. Then it should be possible to estimate the effect of any particular kiln schedule within the bounds covered by the research. An alternative to the generalized approach would be to develop a variety of particular, efficient kiln schedules and evaluate the effect of each on mechanical properties of lumber.

In the general approach, kiln schedules could be selectively chosen to systematically cover different time-temperature regimes of drying. Stepwise rising, continuously rising, and constant temperature schedules need to be covered. At least two and preferably three time regimes and at least three temperature regimes could be studied under each type of schedule.

The number of time-temperature regimes actually covered in the generalized approach will depend on the importance of the mechanical property and lumber species in life-safety applications. Tensile, bending, and compression strength are generally important properties Shear strength is important in some applications. Douglas-fir and

southern pine are generally important structural species but some other species groups (and particularly, certain grades in other species) are also structurally important from a life safety perspective, particularly when machine stress rated. It may be of less importance to make a comprehensive drying study of other lumber species-grade combinations. What these comments do is introduce the concept of priorizing research goals and approaches. This is not easy and we run the risk of offending certain proprietary interests and overlooking the concerns of others. But we cannot evaluate all possible combinations of kiln schedule/species/grade/property. After all, the final result is a concern for engineering properties and this must take into account a practical engineering view of the availability and application of knowledge.

Currently, recommended allowable properties for structural lumber do not recognize different drying procedures. Although Kozlik found no significant difference in bending strength of Douglas-fir and Western hemlock lumber dried at 70° and 170° F, perhaps studies on high temperature drying effects should include air-drying or some low temperature schedule as one condition.

For some species, wet pocket is a common occurance. When lumber containing wet pockets is not segregated from more easily dried lumber, such lumber may be recycled through the dry kiln to satisfy maximum moisture content specifications. The effect of more than one standard kiln schedule cycle on mechanical properties of such lumber should be evaluated.

Researchers conducting studies on high temperature drying effects should have some guidelines so that research results have a comparable basis for comparison. For example, the Coordinating Committee could recommend some relatively mild kiln schedule that could be used for all species to serve as a control condition. Other important guidelines could include the average moisture content to which each kiln change is to be dried, whether there should be an equalizing treatment included at the end of each kiln schedule, and the time that material should be stored under common conditions to attain comparable equilibrium moisture contents. One suggestion would be that final conditioning ought to take several months unless it can be demonstrated by check weights of a satisfactory number of lumber samples that material has come to equilibrium.

This statement of research needs suggests that a comprehensive study of the effects of high temperature drying on mechanical properties of lumber needs to be undertaken. It would seem that several research organizations will need to cooperate in this effort to have the needed results in the hands of the Coordinating Committee by an early date. Several laboratories have some capabilities for drying at high temperatures, although they may not be equipped to perform some of the mechanical tests of lumber, particularly in tension and compression parallel. Thus, cooperative efforts between labs to conduct studies would appear very feasible.

We would be negligent in leaving this topic that has emphasized tests on lumber if we did not dwell further on the significance of

lumber tests vs. tests on small specimens. Small specimen tests have an important role to play and, in fact, may hold the key to identifying phenomena that are barely distinguishable in tests of structural-size material. That, in fact, however, is the justification for a major emphasis on full-size tests as well.

It appears from a number of sources that the so called "grade effect" can profoundly influence what we scientists have often treated as "average" treatment effects on species properties; witness for example studies on duration of load as well as drying. We already have alluded to the need to priorize grade levels but we wish to add the caution that evaluation of the effects of a treatment on a "grade" can be a monumental task. What often is more accessible is a comparative test of the effects of grade within a sampled population. The first demands both a complex and comprehensive sampling program; in the second, sampling is no less important but the scope and subsequent claims are less. These distinctions may appear hazy but careful concern in modeling is very important.

We will close with the further observation that the ability to deal effectively with the probabilistic nature of lumber properties is in its early stage of growth. Yet the advent of probabilistic design in Canada and in the U.S. suggests that research studies from now on must include notions of distribution, sampling adequacy, tolerance, and confidence in order to contribute to tomorrow's needs.

FROM PROCESSING VIEWPOINT

By

J. M. McMillen and E. L. Schaffer

The ultimate goal of processing research in the area of high temperature drying is the identification or development of drying processes that minimize strength loss and maximize drying rate, and that conserve energy and material.

To reach the ultimate goal, we need to know when high-temperature degrade occurs and why. Hence, fundamental research employing small specimens and controlled conditions plus adequate kinetically-based models to guide both experimentation and analysis are in order. Small specimens can be clear of natural defects, eliminating a very hard-to-control variable so that the remaining variables - time, temperature, and moisture content principally - can be defined and controlled to sensitively indicate basic effects. Normal, as well as abnormal (from wetwood), variation in moisture content and drying rates need to be considered. Bacterial infection greatly reduces permeability in some woods and creates zones of persistent high moisture contents. The studies should include temperatures over a broad range.

Since the industry is already using high temperature drying, or variations of it, for a variety of species, studies should be initiated immediately on the engineering properties of full-size lumber by grades used in structural applications. Previous research has shown that high-temperature strength reductions occur with all species, although the reductions appear to be insignificant with southern pine. Since high temperature drying has good

industrial prospects, an acceptable level of strength reduction from some reproducible mild base could be set. Engineering researchers at FPL in the 1940's accepted the "aircraft schedules" as being capable of producing wood having maximum strength with maximum weight. Initial temperatures ranged from 115° to 135°F; final temperatures from 145° to 165°F. These schedules could be used for the base. The "aircraft" specifications also contained control standards for operation of commercial kilns that could be adapted to the high temperature research.

Temperature schedules that could be considered include conventional, elevated, elevated-high, high, and continuously-rising. Besides characterizing the wood by grade and by type, size, and location of defects, it should be characterized as to permeability and form and regularity of moisture gradients or cross sectional moisture distributions.

In a very permeable wood, the internal temperature could remain as low as 212°F for a considerable length of time even when the dryer temperature exceeds 212°F. When drying a very impermeable wood, the moisture may not escape fast enough to prevent pressure build up; so internal temperature will rise above 212°F. Any attempt to define fundamental time, temperature, moisture content effects on strength should be based upon internal temperatures to have any meaning.

If possible, full-size material should be dried in the kiln to the target moisture content customary for the end product. A moisture equalizing period should be used if industry believes it is in the realm of practicability. Otherwise, high temperature drying should be discontinued when some practical percentage of the material has dried to or below the desired maximum moisture content. Then, the material should be stored at 75 to 80°F and appropriate

relative humidities until an agreed upon moisture content is reached. Separate studies can be made on the effects of recycling and prolonged equalization, if necessary.

A reasonable target date should be anticipated for the issuance of an initial comprehensive and authoritative report. June 30, 1979 is suggested. This report would show: a) what species can be dried by specified high temperatures without reductions in allowable design properties, b) what are the best alternative procedures including high temperature segments for the other species to meet the same strength requirements, and c) what reduction in allowable stresses would be needed if high temperature is used directly on one of these latter species. Consideration also should be given to Committee validation of publications of individual research results before June 1979.

IV. SUBSTANCE OF COMMENTS NOT IN POSITION PAPERS

J.F.G. Mackay

Research should not go the "many variables" route. We should be concerned with evaluating what industry is now doing. The products that industry is now producing should be scanned.

Assuming that basic research is carried out on small clear wood specimens, how are the findings to be applied to the different grades and sizes of lumber? There is a possibility that knots and other factors will interact to cause some different strength effect. Perhaps lower grades of lumber are less sensitive to high-temperature drying than higher grades. No blanket statement should now be made that would apply to all grades, due to lack of sufficient research.

We should be concerned about the effects of redrying, for example, in those species prone to wet pockets. There are few data in the literature on redrying.

W. L. Galligan

In general, construction lumber grades are somewhat categorized as to use. The grading system for United States lumber and for Canadian lumber produced for the United States market is essentially frozen in that there is much inertia built into the system. Only minor changes have been made in the past and likely will be made in the near future. Standard-writing bodies have a need for technical guidance. Some strength changes are sufficient to affect the existing system of assigning allowable properties, if based on clear wood processing experiments. However, the same processing effects may not show up when different grades, widths, and lengths of lumber are involved.

For example, 2 x 4's and 2 x 6's in the better grades are specified for truss chords; tensile and compressive strengths parallel to grain and bending strength are of major importance. In the lower grades, those sizes are used for wall studs and truss web members where compression strength and bending strength (studs) are important, but likely at a lower level of criticality than in truss chords. Larger width lumber is generally used as joists where modulus of elasticity has been the most important engineering property.

Each of the use categories of lumber have associated premier lumber lengths. Premier lengths are 16 feet for truss chords, 8 and 10 feet for studs, and 12 to 16 feet for joists.

Grade, size, and use categories are important considerations in deciding on a research program of high-temperature effects. For the joist sizes, we may wish to deemphasize the effects on strength but emphasize the effect on MOE. In the truss lumber sizes, we would stress the strength effect and the interaction of the strength effect with lumber grade. For example, how the strength effect of high-temperature drying relates to lumber strength ratio would be of importance. From the standpoint of evaluating the strength effect, the ideal length of lumber is probably 16 feet. Can research laboratories conduct drying studies on this length lumber? One other point that ought to be studied is the initiating failure mechanism in the tensile or bending test. Is it tension at the start, and then shear? Is the failure mechanism affected by high-temperature drying?

Warren Thompson

Splitting due to toenailing of southern pine studs was less severe in high-temperature dried material than in conventionally dried material.

Regarding additional research on the high-temperature drying effect, one objective should be to determine the effect on small clear wood specimens. The use of full-size pieces containing knots, large grain angles, etc., will likely confound the material aspects of the research. Predrying, such as partial air drying, should be avoided so that studies conducted at different times or by others start from the same base, namely, green wood. There is also a question about the maximum drying temperature. Is 240° F ok, but 270° F not?

D. R. Huffman

On the question of research needs--grouped species variability in strength is a problem. The eastern species are grouped and the lumber is marketed as No. 2 and Better. There is a question about whether the Eastern FPL should do more research on the grading problem rather than on seasoning. It appears that we will do limited seasoning research on high-temperature drying at Ottawa, concentrating on optimizing drying time and degrade effects, but with no great emphasis on the high-temperature drying effect on strength. At Eastern FPL we are initiating a dry-kiln energy-use study. The experimental kiln will be very flexible in that heating can be by steam, gas, or electricity and air speeds can be varied between 200 and 1,100 feet per minute. The kiln will have a 5,000 board foot measure capacity. Both conventional and high-temperature drying will be evaluated.

Regarding experimental procedures, I agree there is a need for test uniformity in processing, equalization, moisture content correction. We should have a standard for equalization, not a moisture content basis. We should be evaluating full-size lumber, not small clears.

C. Skaar

There needs to be some study of the drying kinetics, especially with western species. Southern pine may not be a problem because it dries so rapidly. Western woods present greater problems, possibly because they are less permeable and therefore dry more slowly and rise to higher temperatures at given kiln temperatures.

We can get some fundamental information from clear material, but we can further increase our understanding of the high-temperature drying effect by observing where the specimens fail in relation to knots and other defects.

There should be a standard practice for conditioning specimens prior to strength testing; that is, a standard relative humidity condition should be used for final specimen conditioning, as well as the practice of adjusting results to a standard moisture content.

Peter Koch

Because southern pine trees are harvested on ever shorter rotations, juvenile wood content of southern pine lumber is increasing. This juvenile wood content causes warpage during drying unless the lumber is placed under effective mechanical restraint.

Most kilns for southern pine have high-temperature drying capability, with dry bulb temperatures of 220° to 240° F in common use. Kiln loads are commonly 8 feet in width and unrestrained. Quicker and more uniform drying could be achieved if load width were reduced to 4 feet, and straighter lumber would be produced through application of mechanical restraint.

Our future research should be positive in nature, rather than negative. That is, we should seek processes that will dry lumber quickly with a minimum of degrade. We should emphasize warp control as well as control over strength properties. Participating laboratories should work on major species groups with this objective in mind. A level of acceptable strength diminution should be agreed on--perhaps 5 percent.

In our research, we should attempt to dry to a common moisture content. Perhaps 10 percent is an acceptable level. If strength evaluations are made after drying to 19 percent followed by gradual equilibration to 10 percent moisture content, results will not be comparable with those obtained by initially kiln drying to 10 percent moisture content.

G. L. Comstock

Because of the many variables lumped together in lumber kiln drying research, we must be careful in the use of information developed. We need to avoid alarming industry prematurely, but we should not whitewash any current bad practices either.

Lumbermills have backed away from constant high-temperature drying of Douglas-fir because of degrade. Weyerhaeuser has converted most of its mills to CRT drying; 60 percent of the Company's western lumber and 75 percent of the Company's eastern lumber are dried by CRT. Main advantage of CRT over conventional is in lower drying costs, but in the South lower degrade is also an advantage.

Mechanical properties and drying process research should keep in touch with each other. We need more fundamental information aimed at identifying the effects of temperature, moisture content, and time, no matter how approached in drying. Some questions needing answers are: Why are the strength reductions happening and how can the drying process be controlled so significant strength losses don't occur? Once these questions are answered, the process can be tailored to drying lumber without significant strength loss. Low cost drying procedures are needed and the conclusions of this conference should move in that direction.

I suggest we form a research coordinating committee rather than a research steering committee. Steering implies authority which we don't have.

Ken Bassett

It appears there is a real need to study the basic mechanisms of what is happening during the high-temperature drying of wood.

C. J. Kozlik

The strength properties most studied to date have been in static bending. What other properties should be considered in high-temperature drying research? For example, what effects would high-temperature drying have on shear, compression, and tensile properties of lumber? These are important properties and should be considered.

Reduced equilibrium moisture content due to high-temperature drying has been demonstrated to last a long time. Reduced EMC's were still apparent after 7 years.

Strength evaluations of lumber dried at high temperatures should be well planned because of the large variation in strength. Lumber should be classified by modulus of elasticity or strength ratios before drying so that different kiln runs can be fairly compared. In judging study findings, strength results in the lower part of the range of values should be given due consideration.

C. C. Gerhards

A 10 percent reduction in allowable lumber properties is recommended in the NFPA National Design Specification for Lumber for fire-retardant treatments. Some similar recommendation would be warranted for high-temperature drying where research has indicated such a significant effect; however, there would be problems in identifying high-temperature-dried lumber in practice.

We need to evaluate the effects of high-temperature drying on lumber rather than on small clears. I have observed internal checks around knots in resawn kiln-dried lumber. These checks would affect the strength properties of the lumber, but small clear specimens would not predict the same effect.

Forest Products Laboratory has a study in progress in which we are comparing the tensile strength properties of Douglas-fir 2 x 4 lumber dried under five different kiln conditions. Conventional schedules, stepwise rising temperature schedules, and a high-temperature schedule are included. Restraint while under drying is also a variable.

J. M. McMillen

There have been complaints about dissatisfaction with some high-temperature dried lumber. A southern pine lumber dealer sells both conventional and high-temperature dried lumber but he does not like the high-temperature dried lumber. It seems more brash and completely different from the conventional.

Insurance premiums should be a consideration in high-temperature drying. A kiln manufacturer indicated that three insurance companies would allow entering air temperatures up to 275° F and 290° to 300° F at the motor frame.

There is a problem of getting the kiln temperature up to the prescribed level with research equipment. Although a kiln may be preheated, there can be a considerable time lag after the lumber sample is placed in the kiln before the desired temperature is again attained.

Peter Koch

A portable kerosene burner can be used as an auxiliary heater in research kilns to shorten elapsed time to dry-bulb set point. Burner adjustment is critical in avoiding a soot film on the lumber, however.

E. L. Schaffer

There is a need for high-temperature drying experiments on both small clear wood specimens as well as full-sized lumber.

R. W. Erickson

One difficulty may lie in using small specimen data to estimate the effect on industrial sized material. Some of the research reports on high temperature drying contain reference to the fact that small, clear strength specimens were cut from the larger pieces in "such a way as to avoid honeycomb." The effect of high-temperature drying on clear wood strength may be of secondary importance in some instances if the primary effect of the drying is to destroy the integrity of the structural member at a critical location. Also, we may need to determine what happens in different parts of an industrial kiln as temperature will vary across a kiln load.

V. RESEARCH CONFERENCE CONSENSUS

The consensus of the conference participants was that:

(1) Further basic and applied research on the mechanical properties of high-temperature-dried softwoods is needed.

(2) Insofar as possible, the applied research should be guided by basic research results, but both types should go on concurrently.

(3) There should be as much coordination of the research as possible.

(4) The overall objective should be to develop technically sound accelerated drying methods for structurally important species or groups of species, with strength losses held within agreed-upon limits.

VI. RESEARCH COORDINATING COMMITTEE

Conference participants discussed the various aspects of a research coordinating committee as opposed to a research steering committee. It was felt that a coordinating committee would be the more applicable due to the need to involve many research organizations to solve the high-temperature kiln drying problem. Several of the participants volunteered to be members of the Research Coordinating Committee. Those volunteering were: William Simpson, Graham Mackay, Chris Skaar, Peter Koch, Charles Kozlik, and Ken Bassett.

VII. APPENDIX

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SUMMARY OF REPORTED HIGH TEMPERATURE DRYING EFFECTS ON SOFTWOOD MECHANICAL PROPERTIES

By

C. C. GERHARDS

In preparation for this research conference, the world literature was searched for reported effects of high temperature drying on the mechanical properties of softwoods. A preliminary copy of the reported effects summarized in tabular form was sent to each invited participant. Additional results were subsequently found and a new summary prepared. The more complete summary is the table that follows these introductory comments. References are in the Bibliography given in another section of these proceedings.

The summary table presents the results from a large variety of studies covering several important species. These include various pines, Douglas-fir, western hemlock, western redcedar, spruces, balsam fir, and western larch.

A variety of specimen types were used in the studies. Many of the researchers dried lumber-sized or pole-sized material; however, not all of the material was mechanically tested in the structural sizes. Some of the mechanical evaluations, rather, were based on small clears cut from the larger kiln-dried material. A few researchers made complete kiln-drying evaluations on small clears, perhaps because large experimental kilns were not available.

The table of mechanical property effects also shows a large variety of kiln schedules. Some were constant high temperature, some started at a lower temperature and ended at the higher temperature, while others incorporated organic vapor or superheated steam.

Finally, the basis on which high temperature drying effects could be compared varied with the researcher. Some used air-dry lumber as controls, while others used conventionally dried lumber as controls. Conventional drying included some relatively high temperatures in a few studies. In addition to the type of control variation, some researchers adjusted the mechanical property data to a common moisture content, while others chose to ignore equilibrium moisture content differences.

All of the above variations make for difficult comparison and interpretation of results among the various research results reported.

Mechanical Properties of Softwoods Dried at High Temperatures Compared to Those Dried at Conventional Temperatures

Species	Researcher	Type of specimen	Schedule	Relative property values for high temperature drying schedules: Modulus of elasticity	Modulus of rupture	Shear	Compression parallel	Tension parallel	Comments
(Scots?) pine	Leont'ev	30, 40, 60 mm thick	Lo-Hi 180°-230°F	--	--	0.88 to 0.99	0.91 to 1.04	--	Based on controls
Do.	Schneider	20 mm thick	230°F	--	1.01	--	1.01	--	Based on controls, modulus of rupture unadjusted, compression parallel adjustment to 12 pct moisture content
			266°F		1.05		.98		
			302°F		.96		1.02		
			356°F		.87		.98		
		40 mm thick	230°F		.76		.94		
			302°F		.74		.93		
			356°F		.73		.98		
Scots pine	Comben	Small clears from kiln-dried planks	230°F	1.05	.97	--	--	--	Based on conventionally dried controls
Do.	Leont'ev & Krecetov	3- to 6-cm boards	221°-230°F 232°F superheated steam	--	--	.93 to .94 .95	.96 to .97 1.04	--	Do.
Jack pine	Cech & Huffman	2x6 joists	240°F	.96	.84	--	--	--	Based on conventionally dried controls, adjustment to 12 pct moisture content
Jack pine (see conference proceedings)	Huffman	do.	240°F	.98	.87	--	--	--	Based on conventionally dried controls, adjustment for MOE and to 12 pct moisture content
Lodgepole pine	Lowery & Rasmussen	Rewetted small clears from kiln-dried poles	200°F	.93	.85	--	--	--	Based on green controls
Do.	Troxell & Luza	Small clears from kiln-dried 2x4 studs	220°F	.99	.97	.92	--	--	Based on air-dry controls, adjustment for specific gravity
Eastern white pine	Ladell	Small clears from kiln-dried planks	230°F	--	.95	--	--	--	Based on air-dry controls
Southern pine	Koch	2x4 studs	240°F	.98	.96	--	--	--	Based on conventionally dried controls
Do.	Thompson & Stevens	Small clears from poles kiln dried to 30 pct moisture content	212°F 225°F	1.06 1.13	.92 .86	--	--	--	Based on controls
Southern pine (see conference proceedings)	do.	Small clears from kiln-dried studs	215°-225°F 225°F 235°F	.90 .92 .84	.94 .92 .88	--	--	--	Based on conventionally dried controls

(Sheet 1 of 4)

Mechanical Properties of Softwoods Dried at High Temperatures Compared to Those Dried at Conventional Temperatures--Con.

Species	Researcher	Type of specimen	Schedule	Modulus of elasticity	Modulus of rupture	Shear	Compression parallel	Tension parallel	Comments
				Relative property values for high temperature drying schedules					
Southern pine (see conference proceedings)	Comstock	2x4 joists:				--	--	--	Based on conventional progressive high temperature drying
		No. 1	235°F	0.98	0.90				
		No. 2		.97	1.00				
		No. 3		.98	1.02				
		No. 1	Constant rising temperature to 250°F	1.02	.98				
		No. 2		1.03	.99				
		No. 3		.97	1.05				
South African pine	Merwe	38 by 115 mm	Various up to 239°F	<1.05	>.97	--	--	--	Based on controls dried at 104°F.
		Small clears from 38- by 115-mm material		> .95	>.90				
Douglas-fir	Salamon	Small clears from kiln-dried 2x8's	Lo-Hi 190° to 195° start and 218° to 225°F maximum:			--		--	Based on conventionally dried controls, adjustment for 11 mos..EMC
			Without superheated steam	.92	.87		1.00		
			With superheated steam	.93	.83		.86		
Do.........	Kozlik	Small clears	215° or 230°F	.98	.89	0.84	--	--	Based on air-dry controls.
Do.........	....do.....	2x6's, strength ratio class:	230°F			--	--	--	Do.
		40 pct		1.01	.78				
		60 pct		1.03	.77				
		80 pct		.99	.80				
Do.........	Eddy & Graham	Small clears	Organic vapor drying:			--	--	--	Do.
			190°F	1.02	.91				
			225°F	.96	.82				
			250°F	.99	.79				
Do.........	Graham	4x8's	220°F xylene vapor drying	.94	.54	--	--	--	Do.
		Small clears from 4x8's	220°F xylene vapor drying	.95	.90				
			202°F kiln drying	1.02	.94				
Do.........	MacLean	Small clears	250°F steamed 16 hr	.96	.91	--	--	--	Based on controls, adjustment to 12 pct moisture content
			300°F steamed 8 hr	.86	.85				
Douglas-fir ...... (see conference proceedings)	Kozlik	2x6's:		--	--	--	--		Based on drying at 170°F
		Small knot	200°F					0.92	
			230°F					.89	
		Large knot	200°F					.84	
			230°F					.78	

(Sheet 2 of 4)

Mechanical Properties of Softwoods Dried at High Temperatures Compared to Those Dried at Conventional Temperatures--Con.

Species	Researcher	Type of specimen	Schedule	Relative property values for high temperature drying schedules					
				Modulus of elasticity	Modulus of rupture	Shear	Compression parallel	Tension parallel	Comments
Douglas-fir (see conference proceedings)	Comstock	2x6 joists:				--	--	--	
		Select	230°F	0.97	0.87				Based on conventionally dried controls, adjustment to 12 pct moisture content
		Construction		.96	.86				
		Standard		.95	.82				
		Select	Constant rising temperature to 250°F	.96	1.02				
		Construction		1.03	.94				
		Standard		.96	.99				
Douglas-fir	Ladell	Small clears from kiln-dried planks	237°F	--	.90	--	--	--	Based on air-dry controls
Western hemlock	Salamon	Small clears from kiln-dried 2x10's:							Based on conventionally dried controls, adjustment for specific gravity
		Shipment 1	Lo-Hi 160° to 218°F	1.05	1.02	--	1.06	--	
			220°F	.98	.97	--	.97	--	
		Shipment 2	Lo-Hi 160° to 230°F	1.11	1.17	--	1.17	--	
			220°F	1.05	1.10	--	1.04	--	
Do.	do.	Small clears from kiln-dried 2x4's:							Based on air-dry controls, adjustment for specific gravity
		Series 1	Lo-Hi 160° to 235°F	1.21	.89	--	1.10	--	
			225°F	1.09	.75	--	1.01	--	
		Series 2	Lo-Hi 160° to 225°F	.92	.95	--	1.06	--	
			225°F	.52	.67	--	1.03	--	
Do.	Kozlik	Small clears	215° or 230°F	1.04	.93	0.90	--	--	Based on air-dry controls
Do.	do.	2x6's, strength ratio class:	230°F			--	--	--	Do.
		40 pct		1.01	.95				
		60 pct		.99	.82				
		80 pct		.99	.93				
Do.	Ladell	Small clears from kiln-dried planks	237°F	--	1.00	--	--	--	Do.
Western hemlock (see conference proceedings)	Kozlik	2x6's:		--	--	--	--		Based on drying at 170°F
		Small knot	200°F					0.95	
			230°F					.79	
		Large knot	200°F					1.01	
			230°F					.98	

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Mechanical Properties of Softwoods Dried at High Temperatures Compared to Those Dried at Conventional Temperatures--Con.

Species	Researcher	Type of specimen	Schedule	Relative property values for high temperature drying schedules: Modulus of elasticity	Modulus of rupture	Shear	Compression parallel	Tension parallel	Comments
Western redcedar	Salamon & Hejjas	Small clears from kiln-dried 2x8's & 2x10's:	Lo-Hi schedules:			--		--	Based on conventionally dried controls, adjustment for specific gravity
		Shipment 1	160° to 215°F	1.04	0.95		0.97		
			160° to 225°F	1.02	.98		.97		
			160° to 225°F	1.02	.95		1.00		
		Shipment 2	160° to 225°F	.99	1.00		1.06		
			160° to 228°F	1.01	1.02		1.00		
Do.	Ladell	Small clears from kiln-dried planks	235°F	--	.95	--	--	--	Based on air-dry controls
Eastern spruce	Cech & Huffman	2x6 joists	240°F	.98	.90	--	--	--	Based on conventionally dried controls, adjustment to 12 pct moisture content
Do.	do.	2x6 joists:	240°F			--	--	--	Do.
		Without precompression		.97	.96				
		With precompression		.96	.83				
Eastern spruce (see conference proceedings)	Huffman	2x6 joists	240°F	.99	.89	--	--	--	Based on conventionally dried controls, adjustment for MOE and to 12 pct moisture content
Western spruce	Salamon	Small clears from kiln-dried dimension	Lo-Hi 170° to 232°F	1.04	.97	--	1.02	--	Based on air-dry controls, adjustment for specific gravity
			Lo-Hi 170° to 265°F	1.00	.92		1.01		
			232°F	.98	.96		1.01		
			230°F superheated steam	1.02	.98		.99		
Eastern white spruce	Ladell	Planks (small clears?)	228° to 234°F	--	1.00	--	--	--	Based on air-dry controls
Balsam fir	Cech & Huffman	2x6 joists	240°F extended	.97	.84	--	--	--	Based on extended conventionally dried controls, adjustment to 12 pct moisture content
Balsam fir (see conference proceedings)	Huffman	do.	240°F	.99	.90	--	--	--	Based on conventionally dried controls, adjustment for MOE and to 12 pct moisture content
Western larch	Lowery & Rasmussen	Rewetted small clears from kiln-dried poles	150°F	1.02	.92	--	--	--	Based on green controls
			200°F	.99	.89				

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